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USAAMRDL ltr, 4 May 1971

CAL/TRECOM SYMPOSIUM

PROCEEDINGS Vol III

**Dynamic
Load Problems
Associated
with
Helicopters
and V/STOL
Aircraft**

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JUNE 26-28

STATLER HILTON BUFFALO N.Y.

CAL/TRECOM SYMPOSIUM

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Statements and opinions contained herein are those of the authors and are not to be construed as reflecting the views of the Department of the Army or the cosponsors of this Symposium--The U. S. Army Transportation Research Command or Cornell Aeronautical Laboratory, Inc.

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The formal presentations by each panel member are published herein without editing as well as the formal recommendations of the Helicopter and V/STOL panels, as regards areas of future research.

In addition to the panel presentations, the address given at the banquet by Major General William J. Ely, Deputy Commanding General, U. S. Army Materiel Command, is also published.

Symposium Chairmen

Richard P. White, Jr. (CAL)

John E. Yeates (TRECOM)

HELICOPTER PANEL

PRESENT AND FUTURE HELICOPTER DYNAMIC LOADS RESEARCH

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PRESENT AND FUTURE HELICOPTER DYNAMIC LOADS RESEARCH

Edward R. Wood

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INTRODUCTION

As the helicopter encounters an ever-widening range of tasks, greater demands are placed upon it. More speed is desired, as is improved reliability, lower costs, and better crew environment. To meet these demands, future helicopter development must build upon a firm foundation of understanding of dynamic loads. To this end, Sikorsky Aircraft welcomes the opportunity to submit the following list of research areas to the joint Cornell-TRECOM Symposium on dynamic loads.

The paper is divided into two major parts: Part I, The Helicopter Today, and Part II, The Helicopter of the Future. The majority of research listings are given under the first part. Here, research areas have been further subdivided as shown by Figure (1). Research areas of Part I are obviously strongly interdependent. Most of these apply to future helicopters of Part II as well.

PART I - THE HELICOPTER TODAY

1. Air Mass Dynamics

a. Variable Induced Velocity: Encouraging progress has been made in recent years. Variable inflow is required for accurate blade airload, stress, and fuselage vibration prediction throughout the helicopter's speed range. Recent research indicates that it may tend to localize toward the blade tip in high-speed flight. What is needed from analysis is an accurate and rapid method for inflow prediction. From test, better understanding is sought through such means as flow visualization studies. It is felt this area holds the key to explaining: (a) buildup in vibration levels during transition flight; (b) control stick reversals during transition flight; and (c) reported ability to fly at two power settings during this same speed regime.

2. Prediction of Aerodynamic Loads

a. Unsteady Aerodynamics: This area is linked directly to work in variable induced velocity. What is necessary is to evaluate the significance of unsteady effects as related to present quasi-steady airloads prediction methods.

b. Radial Flow: Generally ignored in airload prediction methods based upon two-dimensional airfoil data, its significance should be evaluated.

c. Transient Conditions: Methods are needed for predicting blade airloads under gust and transient maneuver conditions.

3. Blade Dynamics

a. Rotor System Tests: Considerable testing has been done at airspeeds below 140 knots. What is urgently needed are model or full scale rotor tests at high speeds with conventional rotor systems. Such tests should be designed to provide rotor dynamic information for design of future high-speed or compound helicopters.

b. Blade Root Vibratory Shears: Needed are measurements of and methods to accurately predict.

c. Control Loads: A developed method for predicting control loads and associated control load divergence is sought. Recent studies show that non-linear effects such as local swash-plate flexibility may be important here.

d. Blade Vibratory Stress: Required is a developed method for predicting blade vibratory stresses including full higher harmonic content in both low and high-speed flight.

e. Blade Flutter: What is required is an accepted method for substantiation of main and tail rotor systems for freedom from flutter-type instabilities in forward flight.

4. Blade-Fuselage Coupling

a. Rotor System Impedance: Analysis and test research should be done to define the six degree-of-freedom impedance of a helicopter rotor system including blade flexibility. Coleman's[1] work initially

1. Coleman, R.P., and Feingold, A.M., "Theory of Self-Excited Mechanical Oscillations of Helicopter Rotors with Hinged Blades", NACA TR 1351, U.S. Government Printing Office, Washington, D.C., 1957.

provided this for two hub degrees-of-freedom and rigid blades. The work is needed for better understanding of rotor system stability. It is also required for extrapolation of fuselage ground shake test results to in-flight vibration levels.

5. Fuselage Dynamics

a. Fuselage Vibration Levels: For this requirement, a substantial analytical method is sought which can be used to predict fuselage vibration levels throughout the forward speed envelope.

b. Airframe Fatigue: Improvements are needed in determining fuselage structural characteristics so that better techniques can be developed for designing airframe fatigue strength to dynamic loads. At present it is difficult to properly account for such effects as local skin buckling and fuselage cutouts as related to fuselage dynamic load analysis.

6. Design Criteria

In addition to areas already outlined, further information is required by industry for improved design criteria of helicopters for dynamic loads. Strongly urged is incorporation of a flight history recorder in representative Army helicopters. Automatic data reduction should be provided. The recorder would note basic flight data such as altitude, airspeed, rotor speed, engine torque, and vertical, lateral, yaw, roll, and pitch accelerations. Data should be kept to the minimum. For more detailed information, the flight would be reproduced at the manufacturer's facility. By answering such questions as how far pilots push the aircraft, this data would help determine helicopter mission spectrums. Information would also be of value for establishing an accepted criteria for design load factor. Required load factor versus achievable load factor for the mission could be documented. Also, from this information dynamic substantiation of rotor blades could be carried out. Maneuver and fatigue criteria could be established.

PART II - THE HELICOPTER OF THE FUTURE

There is considerable interest today in extending the speed frontier of helicopters to the 200-300 knot region. The compound helicopter is a possible configuration to meet this requirement. Here, the rotor is substantially unloaded in high-speed flight by external wings, and jet or prop-jet engines provide the necessary propulsive force.

An important variable in compound design is rotor angle-of-attack. This can range from having the rotor tilt forward to provide propulsive force as for the helicopter, to an aft-tilted windmilling rotor which extracts energy from the air stream.

For compound helicopters the following research areas are proposed:

1. An evaluation of the trade-off in vibratory stress, performance, and stability by varying rotor angle-of-attack. Articulated, teetering, and rigid rotor systems should be investigated, and blade twist and planform varied. Studies should be carried out in the speed regime from 200-300 knots.

2. Stability of compound helicopters to gusts and transients should be explored. Here also, teetered, articulated, and rigid rotor systems should be evaluated for airspeeds from 200-300 knots.

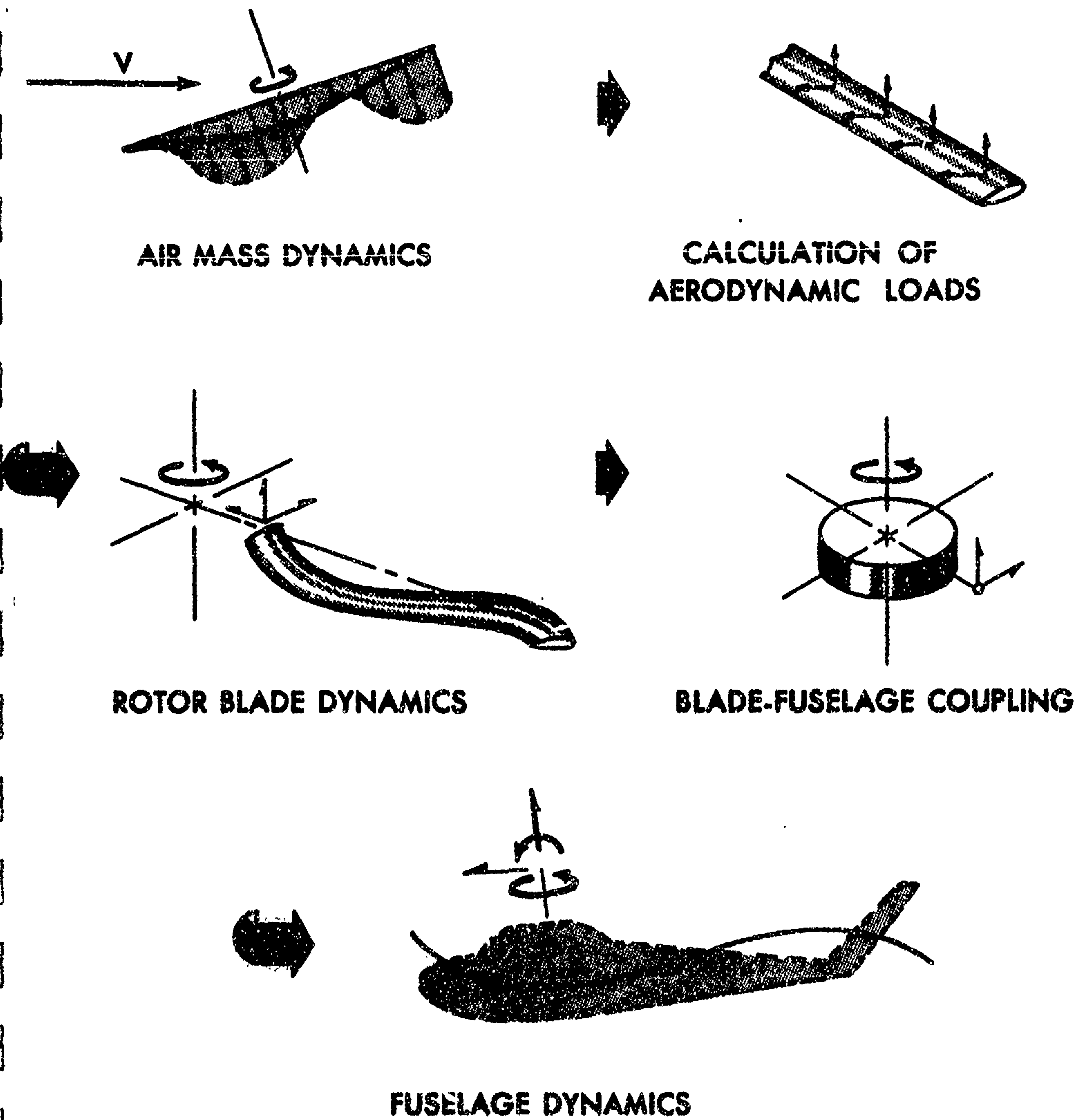

FIGURE 1

STATEMENT OF THE PROBLEM

HELICOPTER PANEL

DYNAMIC LOADS PROBLEMS

Robert Lynn

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Fort Worth, Texas

DYNAMIC LOADS PROBLEMS

Robert Lynn
Bell Helicopter Company

It is seldom that a person is asked to speak on the things which he or his company doesn't know. On the surface, this might appear to be easy. Once you get into it, however, you realize just how many problems and unknowns that we in the helicopter industry work with and face daily. There are so many that for the purposes of a discussion such as this, it becomes a question of what to emphasize.

About the time you decide on what to emphasize you realize that in the short time here, there is the danger of creating an impression that the situation is hopeless - and it isn't - by the way; and you get the rather uncomfortable feeling that what you say might be used against you at some later date. You also wonder whether the various people who are not intimately involved with the problems of our industry, can appreciate the situation. Not from a sophistic attitude necessarily, but from a lack of appreciation of the engineering viewpoint; that is - the acceptance that possibly the problems will be solved or at least contained, without a full understanding of the basic science of the system.

To avoid such misunderstandings, and to illustrate the type of problem which we face, I'd like to discuss briefly the difference between that which we know, and that which we calculate or believe.

We only know the things that exist or which can be measured directly; total power, blade and controls moments, vibrations - these characteristics can be measured <u>after</u> a machine is built.

We can calculate these things, and possibly obtain good over-all correlation between the theory and test; however, at that point we don't <u>know</u> whether each of the various mathematical models and related input data used in the analysis is in itself valid. We only know that the sum total of all of the assumptions, input data, etc., gives an acceptable solution for the <u>particular</u> conditions under study.

A simple example of this is the total power required in forward flight. When the total power is calculated it is broken up into profile, induced, parasite, tail rotor, and other losses. Mathematical models are used to represent each of these components, and each has its own experimental data inputs. The same inputs, of course, are used in further steps to calculate the rotor and controls loads and fuselage vibrations.

Suppose that it is found that the calculated total power is 10 to 20 per cent different from that which you measure. Which component do you correct? Is it the mathematical model or input data of one or all of the components that is in error? Or, is it the measurement? Incidentally, we've found that out of all flight data available, only a very small percentage is acceptable for correlation work.

This is representative of what is faced with the over-all dynamic load problems of the helicopter. It is extremely difficult, if not impossible, to measure and isolate the individual parts that go into the total.

Of course, there are mitigating factors. We are able to effect some isolation of the components by considering different flight conditions and by variations of parameters such as rotor speed; however, until we find some means of fully isolating the various parts of the whole, we are faced with ever expanding and complex computer programs, and endless correlation to establish the validity of our calculation for all operating conditions. Even then, we won't be able to extend those techniques far beyond our flight test experience. This is the primary reason for the need to extend our flight test envelope.

The first problem that faces us then is the need to measure and isolate the various parts of the over-all system which produces the dynamic loads and problems. If we could achieve this, we could refine our mathematical models and input data and achieve a true knowledge of the system with which we work. Whether this can ever be done, I don't know. It certainly should be a goal of our basic research.

Now let's take a look at some of the parts of the over-all dynamic loads problem where our knowledge is insufficient. First, let's consider the basic aerodynamics of a rotor in forward flight.

AERODYNAMICS - Mathematical Model

Induced Velocity Distribution

The mathematical models representing the aerodynamics of a rotor are presently deficient in that we do not have an understanding of the induced flow field created by the rotor. As far as is known there is no experimental work along these lines, probably because no one knows how to do it. Current theoretical work is extensive, however, it's quite involved and is not amenable to an engineering type of analysis. We badly need a simplified approach to the induced flow field. You people who have been working in this area are in the best position to provide this.

We, at Bell, have tried to develop simple approaches to the representation of the induced velocity distribution and have shown, not only significant effects on the air loads distribution, but also have shown that there may be major effects on gross items such as total power. To date, we have not achieved satisfactory correlation with the Bell-TRECOM air load data, and, at this point, we don't know whether to change the system (the mathematical model) or to change the blade lift and drag coefficients to achieve correlation..

Boundary Layer and Skewed Flow Effects

Continuing with the mathematical model used to represent the aerodynamics of the rotor, we still do not include boundary layer effects,

and we break up the airflow over a blade into a radial and normal direction.

The centrifugal pumping action of a spinning disc is well known. The centrifugal pumping action of a rotor blade has not as yet been defined. Perhaps the consideration of this effect would minimize the problems we have in using two-dimensional airfoil data.

As far as the mathematical representation of the airflow over a blade, a better representation might be achieved if we changed the model to consider the total flow over a skewed airfoil section. I believe that this was suggested by Walt Castles of Georgia Tech several years ago. I know of no serious attempt to evaluate his suggestion.

Who is better to cope with problems such as these than the NASA or possibly the various research laboratories of the country.

AERODYNAMICS - Basic Input Data

Even if we had a perfect mathematical model of the aerodynamics of a rotor the empirical airfoil data used in the analyses are inadequate. Two-dimensional lift, drag, and moment data throughout 180° angle of attack, for skewed flow, and with the proper range of Mach and Reynolds numbers are virtually nonexistent - even for the 0012 airfoil.

Obviously, we need to define these characteristics for airfoil sections in current use and just pressing, we need to reinstigate the search for better helicopter airfoil sections. This will become more important as helicopter speeds are increased. I know of no significant work in this area now, and it is sorely needed. This, it seems, should be the work of the NASA.

DYNAMICS

As far as the mathematical model of the dynamics of the rotor is concerned, within the framework of the imperfect state of the art, gross effects on rotor moments can be evaluated. Even here, however, high frequency blade response, the effects of damping and fuselage-rotor-controls coupling are not well defined.

Controls loads calculations are in their infancy. Indications are that controls loads will become the most important problem for high speed rotorcraft. This is especially true whenever the effects of gusts and maneuvers are considered at the higher advance ratios. These things can best be handled by the manufacturers - because it is they who have the over-all problem.

Based on studies at Bell, it is believed that very stiff blades will alleviate the control loads problems and such blades are forecast for all future machines. With stiff torsional blades the primary spring in that system is the controls themselves. Exactly how to handle the dynamic effects of the rotating - nonrotating controls has yet to be developed.

DYNAMICS - Manufacturing Techniques and Hardware Problems

It also should be mentioned that it is believed that a source of many of the high frequency loads usually attributed to induced velocity or Mach number effects can be traced to small deflections or slop in the control system.

Other hardware problems are the predication of the actual stiffness and dynamics characteristics of built-up structures and difficulties associated with making all blades identical.

Determining the actual stiffness of a built-up structure such as a hub, where bearing fits and deflections are important is quite difficult. Things such as these can have large effects.

As speeds are increased, blade manufacturing techniques will have to be improved to avoid 1/rev problems due to out of track caused by small imperfections from blade to blade. Not only are blade contour and twist distribution important, but also stiffness and mass distribution differences from blade to blade will have to be avoided. Incidentally, we at Bell at least, would prefer to fix this problem at its source, rather than depend on complex gadgets.

These things are obviously problems for the manufacturer to handle.

DYNAMIC - Fuselage Response

The effects of fuselage response are familiar to us all. During the past several years a great deal of progress has been made in this area, although it's still quite difficult to build a satisfactory fuselage from the dynamics standpoint when you are attempting to achieve a minimum weight structure. Bell has had some success with an analog approach to the prediction of fuselage response characteristics - also full scale model work has been found to be useful in this regard.

The effects of fuselage response have been shown to be especially important with respect to the tail rotor. We've found that out of track or balance can increase the critical tail rotor loads by a factor of 2 as a result of the anisotropic mounting of the system.

DYNAMIC - Subharmonic and Random Motion

Thus far, I've been speaking of loads, moments, etc., that occur at frequencies which are multiples of the number of blades. There are still the subharmonic and random motion dynamic problems to consider. Such phenomena as weaving, low frequency pylon oscillations which can occur with a soft mounted pylon, and even the old classic ground resonance still cause problems, although they can be contained. Gust excitations can excite the rotor and fuselage and can cause unpleasant motions and vibrations and possibly high structural loads. This will become a further problem as speeds are increased.

Well, gentlemen, I feel that I've barely scratched the surface - but my time is about up. In conclusion, I'd like to say that,

- the helicopter industry does have many problems and unknowns facing it,

- as speeds are increased, these problems will become more severe. The major pitfalls of the future are controls loads and vibrations (including 1/rev). These will be more serious due to the effects of gusts.

- it isn't all black, however, because we will find solutions to these and other problems which are encountered, if not in all cases achieve a complete understanding. To do this,

- we must continue our frontal attack to achieve an understanding of the basic aeroelastic rotor-fuselage-control system. In this regard we need, (Fig)

  - development of means to isolate the various parts of the total problem

  - an engineering solution to the induced velocity distribution

  - additional attention to the basic mathematical models with consideration given to such things as

    - boundary layer

    - skewed flow representation

  - basic airfoil data - C_l, C_D, C_m versus α for R_n, M_n and ψ

  - airfoil development,

  - development of over-all theory,

  - increased efforts on hardware problems; dynamics representation, blade manufacturing, controls looseness,

  - continuing correlation - analysis, model, full scale

This work should proceed in a balanced way - that is, we shouldn't dig a hole so deeply into one particular facet of the over-all problem at the expense of the others. Theory, development, test, and correlation must go hand in hand in an organized - deliberate manner.

Finally, as we work toward an objective of achieving an understanding of the over-all system we must not forget the inventor. We can all show that the bumble-bee can fly, if we use the correct mathematical model - but we must use the right model. We must be careful not to pre-judge inventions, new ideas which will surely come to help solve our problems, only in the light of our own work.

HELICOPTER PANEL

STATUS OF HELICOPTER DYNAMIC LOAD PROBLEMS AT HILLER AIRCRAFT COMPANY

Richard M. Carlson

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STATUS OF HELICOPTER DYNAMIC LOAD PROBLEMS

AT

HILLER AIRCRAFT COMPANY

Richard M. Carlson

With the rapidly increasing yearly utilization of rotary wing aircraft by private operators and the military, and with their introduction to the general public an accomplished fact, the demands for reduced operating costs and passenger-crew comfort are stimulating engineering efforts in previously de-emphasized areas. Much of this effort has been directed toward improving techniques for predicting those dynamic loads which, when measured during flight tests, limit the service life of expensive rotor, control and drive system components. Additional effort is also being directed toward improved methods of isolating passenger-crew compartments from rotor induced dynamic loads. It is the purpose of this paper to present the status of several such efforts which have been initiated at Hiller Aircraft and to discuss certain problem areas which appear to be of significance in the immediate future.

A. Rotor Blade Elastic Response To Transient Control Inputs

When one considers the loading spectrum (i.e., F.A.A. or military) which must be employed to determine main rotor and control system component service life, it is at once evident that stress levels experienced in trimmed flight regimes must be under established endurance limits or successful component design has not been accomplished. The high percentage occurrence (i.e., 92%) of trimmed flight regimes and the fact that loads are experienced in such components at integer orders of main rotor RPM simply means that damaging stress levels cannot be tolerated in such modes of flight. Thus, it follows that if main rotor and control system components do, in fact, exhibit finite service lives, they will do so as a result of loads experienced in accelerated maneuvers which represent

approximately 8% of the flight spectrum. Further, it has been the experience at Hiller Aircraft that finite life of main rotor and control system components results primarily from three accelerated flight maneuvers: (1) cyclic control system reversals, (2) cyclic and collective pull-ups, and (3) autorotation flares.

During the development of the rotor system for the XROE-1 one man helicopter and later during the early flight tests of the UH-12L direct hydraulic controlled rotor, it became quite apparent that rotor systems which were completely adequate for trimmed flight could well be woefully inadequate when subjected to accelerated maneuvers. Recognition of this fact stimulated the initiation of a comprehensive dynamics program directed toward producing analytical methods which would predict rotor and control system loads which result from "ramp" type cyclic, collective and cyclic plus collective control inputs.

To date this program has produced successful methods for predicting transient chordwise moments due to cyclic control reversals and transient flapwise moments due to single "ramp" type collective control inputs. The correlation between measured and predicted rotor bending moments due to this type of separate control input has been very gratifying. However, attempts to predict flapwise and chordwise rotor bending moments and control system loads have not been successful for the simultaneous application of cyclic and collective pitch; the predicted values in many cases being somewhat below the measured values. A substantial analytical effort is still required in this area if reliable methods are to be developed for predicting rotor blade elastic response due to simultaneous application of cyclic and collective control inputs.

B. <u>Non-Linear Transient and Steady-State Response of Drive Trains</u>

While not strictly a dynamic loads problem, but rather a dynamics design problem, the inability to predict the behavior of drive trains which contain non-linear elements has, in the past, resulted in designs which have exhibited

unacceptable dynamic torque levels. This problem is inherent in a majority of helicopter drive train designs as a result of the non-linear stiffness characteristics of conventional over-running clutches and the dynamic characteristics of such drive systems vary substantially with the power transmission level.

Experience at Hiller Aircraft has indicated that reasonable predictions of the low, coupled, branch frequencies and associated mode shapes can be made by linearizing the mathematical description of the drive train and applying conventional torsional analysis methods. However, attempts to predict transient and steady-state response utilizing the linearized system, and limited attempts with piecewise linear systems, have proved to be completely unsuccessful. Practical solutions to problems of this character have been obtained by enlisting the aid of Analog Computer equipment and/or by a "symptomatic" type of analysis and test which is only slightly more sophisticated than the "trial-and-error" procedure. While such practical solutions are nonetheless valuable as a result of this type of engineering, they rarely produce the physical insight necessary to avoid such problems in the next design.

It is recognized that considerable progress has been made recently in analysis of multiple degree of freedom systems containing non-linear elements but this progress appears to have dealt almost exclusively with the homogenous problem. It is felt that study of the transient and steady-state response of, say, a statically coupled three degree of freedom system with just a <u>single</u> non-linear element would be of great value in the design of helicopter drive trains.

C. Isolation of Rotor Induced Dynamic Loads

Efforts at Hiller Aircraft Company to provide improved passenger-crew comfort fall into two distinct categories: (1) investigation of various means of reducing the velocity, or μ, dependent 2/rev vertical forces which originate in a two blade rotor, and (2) investigation of various means of reducing passenger-crew compartment response to 1/rev in-plane, forces which originate in a two blade rotor.

In the first category, considerable effort has been expended in investigating blade root shear response to 2/rev aerodynamic loadings of various radial distributions. These investigations included systematic variations in blade mass and stiffness distribution and have produced valuable design data which may be utilized to minimize 2/rev blade root shear. Further, a significant investigation has been conducted, as is the case with other helicopter manufacturers, which deals with the reduction of 2/rev aerodynamic loadings by means of higher order cyclic pitch application.

In the second category, significant knowledge has been developed regarding direct isolation of the passenger-crew compartment from the effects of the 2/rev horizontal (in fixed coordinates) force which originates in a two blade rotor. Past practice at Hiller Aircraft Company has been to select rotor-airframe isolation springs on the basis of a dynamic analysis which separates the pitching and longitudinal degrees of freedom from the rolling and lateral degrees of freedom. While this analysis includes the effects of various rotor modes of vibration and lateral and vertical fuselage modes of vibration, it tacitly assumes isotropic isolation springs and fuselage inertias, for otherwise the decoupling indicated above would not occur.

Several practical applications of the analysis indicated above have been made in recent years with reasonable success; however, lack of correlation between analytical and experimental results, in one particular application, raised questions as to the validity of the analytical means of prediction. As a result of this, it was decided to verify the questionable analytical procedure during the OH-5A isolation system design. This was accomplished by producing an acceptable isolation system, by the standards of the analytical procedure, and then comparing it with a similar design produced from a direct analog computer study which did not incorporate the assumptions of polar symmetry in the isolation springs and fuselage inertias.

The isolation spring requirements produced by both methods outlined above were practically identical. Normalized response plots produced by both methods, at the pilot and crew stations, were compared and found to be essentially the same in the region of isolation spring stiffness required to effect adequate isolation. However, this correlation existed only in the region of "soft" isolation springs, the term "soft" being indicative of the relative ratio of pylon frequency, in pitch and roll, to the first rotor blade in-plane frequency. In the so-called "soft" spring region, the mast motion was essentially circular even with the ratio of roll to pitch spring stiffness varying between .1 to 3.00. As the springs were "stiffened" the motion of the shaft would become decidedly elliptical, as would be expected; and, further, as the uncoupled frequency of the pylon in the mode normal to the direction of the 2/rev shaft force approached the first rotor blade in-plane frequency, correlation between the analog computer results and those of the analytical procedure disappeared rapidly.

While the basic purpose of the analog computer study was to justify the use of a rapid, far less expensive analytical method, which it did, it also indicated that limited knowledge exists regarding the force dynamic behavior

of a system consisting of a large rotating mass connected elastically by non-isotropic springs to a mass which lacks inertial symmetry.

Recent preliminary design studies at Hiller Aircraft Company have dealt with rotors which are propelled by tip mounted turbojet engines and high speed rotary wing aircraft which employ auxiliary thrust means in combination with the main lifting rotor. Several dynamic load problem areas are anticipated as a result of these design studies and are presented below.

A. Rotor Pitch-Chordwise Coupling Due To Rotating Tip Mass

The dynamic loads problems arising from the installation a relatively large, stationary mass at the tip of a rotor blade have been quite thoroughly investigated and appear to produce no design limitations. When a portion of this mass is no longer stationary, relative to the blade, as is the case for a tip mounted turbojet engine, additional gyroscopic moments occur at the rotor blade tip. The most obvious of these gyroscopic moments is the steady blade twisting moment which is proportional to the product of the turbine wheel angular momentum and main rotor angular velocity. Existence of this steady moment, as in the case of the stationary tip mass, simply imposes additional design considerations on the rotor but does not present fundamental design limitations.

A potential problem area which has not, as yet, been subjected to rigorous analytical treatment concerns the dynamic behavior of the rotor in the presence of the complete gyroscopic coupling which exists between the rotor blade pitch and chordwise motions. Preliminary analyses have indicated that the rotor blade is stable under the action of such coupling; however, the effect of this coupling on the dynamic response to cyclic and collective transient control

inputs and on stall and classical rotor flutter boundaries needs much further investigation.

B. Super Critical Speed Drive Shaft Design

The obvious weight and shafting support vibration level advantages of super critical shafting designs have always been extremely attractive to the designers of helicopter drive trains. Adequate techniques exist for predicting the critical speeds of such shafting designs for variable mass distributions, variable length spans and variable support stiffnesses. And, it should be noted that recent work accomplished at Battelle Institute has produced valuable insight into the damping requirements of a shaft which is to be operated above one or more of its critical speeds.

Existing, successful, supercritical shafting designs in helicopters and VTOL aircraft have generally required lengthy development periods with attendant schedule and funding problems. These lengthy periods could be reduced substantially by increased analytical and experimental efforts, similar to those at Battelle, which would produce methods for predicting the damping required at critical speed to produce specified support load levels for shafting which has specified azimuth versus length diameter run-out distributions.

C. Dynamic Characteristics of Clutching and Declutching Devices

The detail mechanics of engagement and disengagement of starting and over-running clutches in helicopters has been treated rather lightly by the dynamics engineer in the helicopter industry, that is, until a particular design produces engagement or disengagement loads which are in excess of those for which the system is designed. At such a time the suspect clutch is re-evaluated and it becomes immediately evident that its behavior cannot be explained by reducing it to a spring, mass and damper and by analyzing it as

a linear system. With reluctance, the "symptomatic" analysis-test cycle is initiated, the dynamics engineer attempts to simulate the clutch and all of its non-linearities on the analog computer and new vendors are immediately investigated. Sometime later a solution is evolved and the subject of clutch dynamics is de-emphasized in favor of other current problems.

While the above procedure does produce satisfactory solutions, it does little to equip the dynamics engineer for future assignments. This is especially so when one considers the clutching and declutching requirements of various high speed rotary wing configurations which employ auxiliary rotors that have intermittent operational requirements. A prime example of such a device is the tail propeller for the XC-142 VTOL aircraft. This propeller must be accelerated from zero to full RPM in not greater than 10 seconds, at flight speeds of zero to 150 kts. and with inflow angles which vary from zero to 45°. Further, the propeller must be disengaged and decelerated from full RPM to zero under essentially the same environment conditions.

Expensive, lengthy development cycles will continue for starting and overrunning clutch devices until their detailed dynamic behavior during initial engagement, full engagement and final disengagement can be predicted with confidence during the initial design stage.

HELICOPTER PANEL

DYNAMIC LOADS RESEARCH

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DYNAMIC LOADS RESEARCH

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INTRODUCTION

Improvement in the prediction of dynamic loads and fuselage response has been the goal of a major research effort at Vertol during the past several years. Dynamic blade loads for current design are adequately predicted using existing analytical procedures in conjunction with empirical factors developed from past history. Fuselage response predictions using existing methods are much less encouraging. This results from the inadequate phase prediction using the empirical method and the fuselage model not properly simulating the aircraft structure in the dynamic response analysis.

Maintaining the competitiveness of the helicopter for future requirements necessitates improving the vibration and performance characteristics of present helicopters. Further, the improved characteristics must be maintained for future helicopters with speeds above 200 knots and greater load carrying capacity. These requirements for future helicopters can only be accomplished by an improved understanding of the dynamic loads and the resulting fuselage response. Toward accomplishing this goal, Vertol Division, The Boeing Company welcomes the opportunity to discuss present and future research at the joint Cornell-TRECOM Symposium on dynamic loads.

Part I of this paper presents (1) the analytical programs currently in use at Vertol for the prediction of dynamic loads and response, (2) model testing to optimize future rotor system and blade configurations and (3) flight test load measurement to check analytical procedures. Research areas for future helicopters not currently under investigation are presented in Part II. In addition current research must be continued and expanded for future development of the helicopter.

Part I - Dynamics Loads, Present Status

1. Analytical Methods

   A. Rotor System Loads

      Leone Myklestad Bending Moment Program - This program computes blade shear forces and bending moments from flap and lag bending aeroelastic vibrations. The analysis provides the solution at a given condition of forward flight for the zero and first three rotor harmonic of a blade with infinite torsional rigidity. Flap bending theory used in the analysis is given in the A. H. S. Tenth Annual Forum, May 1954; chord bending theory is presented in the A. H. S. Eleventh Annual Forum, May 1955.

Associated Matrix Bending Moment Program - The Associated Matrix program for computing rotor blade loads, vibratory hub loads, and control loads was developed under a Navy Contract. In this program, the blade properties, and aircraft trim data from a separate program are used to solve the aeroelastic equations for the steady and first four harmonic load terms. Torsional flexibility of the blade and root pitching stiffness of the control are included in the solution. Flap and chord bending theory of the analysis are presented in Reference 1.

Advanced Rotor Loads Program - The Advanced Load program extends the basic method used in the above Associated Matrix program to include the effects of stall, compressibility, reverse flow, and azimuthal variation of the root pitching control system. Steady and ten harmonics of the rotors are obtained in the solution.

B. Induced Blade Velocities - Helicopter airloads corresponding to the change in rotor induced velocities are obtained in the rotor load analysis by using downwash velocities computed from the theory developed by R.H. Miller. In computing the rotor downwash velocities, a spiral non-rigid wake was considered and the non-stationary flow effects introduced for the three dimensional rotor in forward flight. A detailed discussion of the theory is presented in the Journal of the American Helicopter Society, Vol. 7, No. 2, April 1962.

C. Fuselage Analyses

Associated Matrix - Matrix programs are currently used to compute the uncoupled vertical-longitudinal and lateral-torsion natural frequencies, free and forced response of the fuselage. The program was developed under an Air Force Contract. Program details, and methods of solution are presented in Reference 2.

COSMOS - A program for analyzing helicopter structure using the stiffness method is currently being used. In the stiffness method of analysis, a compatible set of deflections are determined which satisfy equations of equilibrium. A stiffness matrix for the entire fuselage is completed by a simple summation of stiffness matrices representing each element of the structure. Inversion of the stiffness matrix yields the flexibility matrix or matrix of deflection influence coefficients. Mass properties are combined with the flexibility matrix to form the dynamic matrix, the solution of which is performed to obtain natural frequencies and modes. References 3, and 4 provide a detail description of the program and application to the solution for a shell structure.

D. Rotor Fuselage Coupling

Coupled Vertical-Lateral Matrix Program - The coupled matrix program is an extension of the uncoupled analyses for vertical-longitudinal and lateral torsion. Coupling between the vertical and lateral directions is treated by an elastic element which permits (1) frame distortion in combination with bending, shear, and torsional stiffness properties, (2) attachment of a coupled vibration system such as the flexibly mounted engine, and (3) a six degree-of-freedom impedance of the rotor system. Reference 5 presents a detailed description of the coupled matrix program.

COSMOS Program Including Rotor Coupling

Coupled rotor-fuselage natural and forced response are currently obtained using generalized coordinates to couple the two systems. Rotor impedance including blade flexibility is defined as a function of the six degrees-of-freedom rotor hub. Since model data from the COSMOS fuselage analysis provide similar six degrees-of-freedom motion at the hub, the additional energy of the system can be defined in terms of the hub motions. Equations of motion for the coupled system are solved for natural and forced response using an IBM 7090 computer.

2. Model Testing

Model Blade Tests - Model blade tests are being conducted in the University of Maryland wind tunnel. Rotor loads data from the current tests will be used to,

(a) Define the relative effect on vibratory hub loads of μ, M_t, and C_t/σ for advanced blade designs

(b) Evaluate the effect of advanced blade designs on vibratory hub loads

(c) Define the relative effect on blade loads of μ, M_t, and C_t/σ for advanced blade designs.

3. Flight Testing

A. H-21 Rotor Load Measurement - Steady and vibratory rotor loads for the H-21 helicopter at various forward speeds, rotor rpm's and at two gross weights are available from a test program conducted at Vertol under Air Force Funding. A paper is included at this meeting on the load measurement program. Reference 6 is a report on the measurement program.

B. Load Correlation Study - Flight data on blade and control loads from current production models is being used in an extensive analytical vs test correlation study. It is intended that from the results of this study, existing analytical methods may be improved to provide adequate means for the prediction of rotor loads for high speeds.

Part II - Dynamics Loads, Future Research

1. Analytical Method

   A. Coupled Fuselage-Blade Analysis - For high speed helicopter design study, analytical capabilities must be extended with a coupled fuselage-rotor program that includes,

      (1) blade loads resulting from rotor hub motion

      (2) control feedback from fuselage response

      (3) nonuniform downwash with a reverse flow correction

2. Model Testing

   A. Blade Model Testing - Wind tunnel tests of models should be performed to investigate the effect of twist, planform and airfoil section on control loads, blade load, vibratory hub loads and flutter characteristics.

   B. Rotor System Testing - Model testing should be further extended to include a feasibility study for new rotor concepts. Articulated, teetering, and rigid rotor should be investigated for the effect on rotor loads, control loads, vibratory hub loads and flutter characteristics at μ, M_t, and C_t/σ contemplated for future helicopters. Test research should be used to define the mechanical impedance of the rotor system.

3. Wind Tunnel Testing

   A. Full Scale Wind Tunnel Test - Tests should be performed on a full scale instrumented rotor in the wind tunnel. The data obtained from this type of testing would provide necessary information for the design of rotor systems for high speed flight.

4. Flight Test

   A. Flight Research Program - A flight test program should be performed to establish basic knowledge of the sources of vibratory load and response. In-flight shake testing would be a necessary part of the program to define the aircraft frequencies of peak response for comparison with the calculated natural frequencies. From previous experience, aircraft instrumentation would be necessary for the measurement of,

      (1) blade airloading

      (2) blade motion

      (3) blade loads

      (4) control loads

(5) control position (rotor and cockpit)

(6) rotor hub motion

(7) rotor loads (vertical and in-plane)

(8) fuselage response

From the flight program, the increased understanding of the vibratory load response would permit an increase to maximum speed without limitations due to excessive vibration, and provide dynamic load data for improvement of existing analytical techniques.

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HELICOPTER PANEL

HELICOPTER DYNAMIC LOADS RESEARCH REQUIREMENTS

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HELICOPTER DYNAMIC LOADS

RESEARCH REQUIREMENTS

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INTRODUCTION

As helicopter requirements grow in speed, range, and payload capabilities, it becomes apparent that additional information is required to give the next step in growth a sound and logical basis. Listed and discussed briefly below are those areas which the author feels are most pressing needs for the next generation of rotary wing aircraft. The areas are grouped loosely according to the aircraft components most closely affected by the new knowledge required.

GENERAL DESIGN CRITERIA

1. To maintain maximum design efficiency, the flight profile and loading spectrum for the aircraft must be well-defined. Presently available data in this area is not based on present-generation vehicles. Collection and analysis of sufficient statistical data to establish up-to-date profiles for a variety of missions is an urgent requirement, as is the establishment of reasonable means of extrapolating these profiles to expanded mission requirements.

2. In the light of new loading spectra and recent advances in the knowledge of material fatigue characteristics, substantiation requirements need to be reviewed and up-dated in order to provide most rapid and economical programs consistent with the advances in speed-altitude-gross weight envelopes. An example of an area of potential improvement is in drive system testing, where application of fatigue test techniques may result in significant improvement in reliability for a given test time or reduction in test time to a given level of reliability.

ROTOR SYSTEMS

A. Aerodynamics

1. An accurate and adaptable means of inflow calculations is needed to enable analytical design of rotor systems for higher speeds and modified operating regimes (compounding). Commonly used methods, which recent work show to have substantial errors, are of dubious use when attempting to investigate the effects of twist, planform, blade loading, airfoil section, and other pertinent rotor characteristics on an expanded flight envelope or in unexplored flight regimes.

2. Adequate airfoil data over the range of RN, M and C_L typical of helicopter operation is needed, along with more complete understanding of the effects of the helicopter environment (radial flow, reverse flow) on these characteristics. Development of new sections having improved C_L and M_{CRIT} has been very slow; more efforts in this area would appear desirable.

3. Rotor-rotor (both main and auxiliary) and rotor-fuselage interactions continue to merit study and experimental investigation. Both aircraft drag and aircraft dynamic stability are significantly affected by these interactions.

B. Dynamics

1. Analysis and limited experimental data indicates a marked influence of control system flexibility/rotor mass balance on rotor vibratory airloads. Additional work is recommended to define completely the usefulness of such techniques and the compromises on other systems (control loads, for example) caused by such operation.

2. The use of various schemes for increasing helicopter speed capabilities, such as higher harmonic control and forced lead-lag, has an obvious influence on rotor system loading. Continued efforts to define this influence, which may be sufficiently large to make the device impractical, are required.

3. Rotor dynamics and aircraft handling qualities are closely related. Continuation of investigation programs which concern this interaction (such as rigid rotors) should be continued.

DRIVE SYSTEMS

1. Research and development leading to improved high-speed flexible couplings is important from a maintenance and reliability standpoint.

LANDING GEAR/AIRFRAME

1. Design methods need to be developed and refined for relating aircraft characteristics and required height-velocity envelope limits. Present techniques are largely empirical and do not provide adequate means of forecasting behavior in this critical area.

CONTROL SYSTEMS

1. As helicopter speed requirements are extended, and as various configuration modifications are introduced to achieve these requirements, the aircraft control systems are also going to change. These control system changes will be required either by virtue of the configuration changes or to provide adequate handling qualities. The influence of these changes on aircraft operational loadings will be significant, and both analysis and experimental investigation are required to define this influence (as well as to define the type of control system required).

V/STOL PANEL

DYNAMIC LOAD PROBLEMS ASSOCIATED WITH V/STOL AIRCRAFT

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DYNAMIC LOAD PROBLEMS ASSOCIATED WITH V/STOL AIRCRAFT

William F. Meyer

Summary

In recognition of (1) the new generation of aircraft capable of vertically rising, hovering and cruising at high speed, and (2) the latest advancements in the helicopter and its improved performance, the Army and the Cornell Aeronautical Laboratory through their jointly sponsored symposium wish to give visibility to those dynamic load problems that are unsolved. In response to this effort to further the advancement of these aircraft, this paper has been prepared for the V/STOL panel meeting and covers an outline of current and potential dynamic load problem areas associated specifically with this type aircraft. Since the Curtiss Division has considerable experience in the field of propellers and presently is engaged in the development of the X-19 VTOL airplane utilizing tilting propellers, only propeller driven V/STOL aircraft will be considered.

It will be noted that many of the dynamic load problems of the VTOL covered herein deal directly with those generated by the propeller itself. But, these loads are influenced by the multiplicity of environmental attitudes, mounting flexibility and control conditions brought about by this type aircraft throughout its flight range. This further substantiates that propeller loads play a major role in the over-all structural design of this type aircraft and in its performance; the capability must be developed, therefore, to accurately predict these (and other) loads in the new environment of VTOL operation.

Introduction

Theoretical and experimental research investigations on rotor and propeller driven aircraft in the past have provided valuable information on the dynamics of the aircraft system and service background has supplemented this knowledge. This experience has permitted the evolution of sound procedures for the prediction of environmental loads, the analysis of aeroelastic response and the structural analysis of such aircraft and its components.

Within the past few years new types of propeller driven aircraft have been designed, built and tested. These are VTOL configurations and with them have come some dynamic problems associated specifically with the particular aircraft design, its control system, power transmission system and propulsion system. Whether they be tilt wing or tilt propeller types, these aircraft hover and fly in an early transition regime similar to the helicopter. Therefore, certain dynamic loads on the airframe and the propellers are allied with helicopter and rotor loads. Also, since the VTOL aircraft is trimmed for high speed flight, dynamic loads are similar to those of an airplane and must be evaluated accordingly. While considerable background exists for these regions of flight, the intermediate flight regime is open for considerable refinement in theoretical approach and evaluation techniques.

In the follo brief treatment of some of the dynamic problems of the propeller driven VTOL, the propeller is considered to be of the conventional type, that is, non-articulated, without cyclic pitch and with possibly built in forward blade tilt (cone angle).

Outline of Problems

1. Prediction of propeller generated wing dynamic loads.
2. Prediction of transmission system vibratory torsional loading.
3. Prediction of severity of blade stall flutter during vertical descent.
4. Determination of propeller-mounting system coupled resonant frequencies.
5. Determination of whirl stability characteristics of elastically mounted system of propeller, nacelle and wing.
6. Specification of design dynamic loads for V/STOL airplanes.

These problems are described more fully in the following:

1. Propeller Generated Wing Dynamic Loads

The major forced vibration governing the design of modern propeller blades is the first order excitation (1xP). Methods for predicting this loading for propellers on conventional airplanes were developed years ago. For these propeller applications, the operating shaft angles were low and the 1xP excitation was found to be proportional to Aq (the angularity of the air entering the disc times the dynamic pressure of the free stream). Correlation between calculated and measured 1xP blade shank stresses and shaft loads are within 15% of any of a series of aircraft. In general the shaft loads generated by the vibrating blades are steady loads consisting of a vertical force and a yawing couple.

In consideration of the VTOL aircraft, the theoretical approach was modified to cover the complete shaft angle range. This method was successively refined to improve correlation. In the very high (75° to 90°) shaft angles, the correlation between test and theory is good and the predominant shaft loads generated by the 1xP excitation are a steady force and a steady pitching moment. Intermediate shaft angles involve consideration of several basic flow fields about the propeller and maximum excursions of angle of attack which approach the stall condition of blade sections. Although the procedure is a continuous one throughout the 90° shaft range, there is

room for considerable improvement in predicting loads in this intermediate range of shaft angles, i.e., 30° to 75°.

The major loads and moments imposed on a VTOL airplane structure during take-off, hover and transition are these propeller loads and they influence the:

a. Design of the wing and carryover structure
b. Stability and control considerations of the aircraft
c. Aeroelastic coupling with wing loads
d. Design of the propeller shaft and mounting structure
e. Design of the blades themselves in fatigue.

The success of a method of calculating the propeller dynamic loads, the major component of which is 1xP, depends entirely on the accuracy in the evaluation of the flow field into the propeller. The latter must include the effects of wing attitude, ducts, lead edge flaps, propeller slipstream, etc. Accuracy in the prediction of the flow-field, therefore, remains a major problem in the solution of loads. Once the flow-field has been established the following can be accomplished:

a. Determination of cyclical aerodynamic loading along the blade span and about the disc.

b. Separation of harmonic components (1xP, 2xP, etc.) at each azimuth angle and calculation of blade response to these excitations.

c. Evaluation of resultant shaft loads.

The above work is strongly encouraged and is presently continuing at Curtiss with attention being focused in the evaluation of the flow-field. This approach is significant as it is realized that the higher harmonic components are becoming more predominant in the VTOL aircraft and these components will be automatically evaluated along with the 1xP component.

2. <u>Transmission Vibratory Torsional Loading</u>

The design of a power transmission system is completely dependent upon the steady and oscillatory torsional load schedule considered representative

of the planned installation. Material selection for the various components and choice or sizing of these elements are made on the basis of this load cycle and a required operational or overhaul life of the system.

Oscillatory torque is produced primarily by variations in steady torque to the nacelles to effect necessary control for pitch, roll and yaw during take-off, hover and transition. It is not sound practice to be overly conservative in establishing a design torque loading schedule of a system for which minimum weight is sought. Conversely, an arbitrary loading may lead to a structurally inadequate system. Procedures should be developed to allow realistic load schedules to be established early in the design phase. This will permit a transmission design to be as close to optimum as possible for the installation intended and minimize surprises later in the program.

In those cases where data is available on an operational aircraft and a reasonably similar configuration and mission is being contemplated, the task of arriving at representative control torques may be simplified. That is, if a control power time-history has been recorded and the differential power can be identified with pitch, roll and yaw commands, a reasonable approximation can be made by scaling these power variations to the equilibrium power and inertia of the new vehicle and possibly adjust to a new mission profile.

At this time, however, a very limited background is available on operational aircraft to gain the pertinent data described above. For this reason, and considering the importance of this subject, the following is recommended:

a. Establish on paper a series of V/STOL aircraft to cover the range of size, gross weight, mission capability and performance that will be of interest into the forseeable future.

b. Make a parametric study of the stability characteristics of the above V/STOL configurations selected utilizing analog output to gain performance data, i.e., incremental control power amplitudes and percent time of application.

c. Non-dimensionalize results of item b. for presentation in a chart format for use in design activities.

d. Survey operational V/STOL aircraft for the above information and similarly reduce characteristic data for correlation and verification with theoretical investigation.

This will equip the designer with the basic vibratory loading necessary for him to specifically tailor the various elements of the transmission system to the aircraft under consideration.

3. Blade Stall Flutter

This form of vibration primarily involves the fundamental torsional mode of the blade. It occurs when the blade is operating at conditions such that the angles of attack over a major portion of the span are in the vicinity of the dynamic stall of the sections. Stall flutter became a structural design criterion in those metal blade propellers wherein the design power loading was high and/or the tip speed was low and the over-all blade was compromised for high speed performance of a conventional airplane installation. Therefore, the conditions of stall flutter would arise during static operation at or near the maximum power of the engine. However, during an actual take-off condition, flutter would exist for only a short duration and associated torsional stresses would diminish rapidly with reduction in angle of attack as the airplane accelerated along the runway. High reduced frequency of the blade is the major deterrant to stall flutter.

This vibration is basically an aerodynamically self-excited mode; the damping in the system, however, is such that there is no rapid build-up of amplitude to destructive proportions, a concept usually associated with classical flutter. Rather, there is a gradual increase in the stress level similar to the response of a damped system approaching a resonance.

Stall flutter has not been observed by this Company in their blades designed for VTOL application. The reasons are that:

a. The blades are specifically tailored to satisfy a high static thrust and as such operate at lower power loadings. Blade section operating angles of attack are well removed from their stall condition.

b. The torsional frequency of the fiberglass blades is very high, i.e., two or three times the frequency of metal blades.

c. The damping of the blades is high.

Although stall flutter would not be expected in these blades at take-off even at the higher powers contemplated of future VTOL aircraft, it is a condition that deserves watching. However, the condition of power-on vertical descent involves a complex flow field through the propeller disc, a flow which is further influenced by the presence of the wing and fuselage in this let-down attitude. It is this condition that deserves exploration for future propeller driven V/STOL aircraft.

4. Coupled Resonant Frequencies

Damping is relatively low in the conventional propeller and mounting system even in the lower modes of blade flexural vibration. Therefore, blade stresses can reach levels well in excess of the fatigue strength at or very near resonance. For this reason, adequate rpm margins with respect to these resonant frequencies and operating rpm's must be maintained for blade structural fatigue life. Since operating rpm's usually are predetermined, it is the resonant frequencies that must be adjusted through blade stiffness and mass distributions. Therefore, it is necessary to be able to accurately predict and properly locate by theoretical procedures the major resonant frequencies early in the design stage.

Procedures for predicting these characteristics have been developed and have been in use for years by the propeller industry and for the conventional propeller application correlation with measured data has been good. In these instances, however, the propeller mounting stiffness has been high and in those modes wherein the vibrating system consisted of the propeller, engine and nacelle, the resonant blade frequencies were reduced

only a relatively small amount with respect to fixed root frequencies. That is, with few exceptions, coupled vibration was not a significant design parameter. Note that some modes of vibration cause no reaction on the propeller shaft and are referred to here as fixed root frequencies. The first flatwise or first edgewise (in plane) bending modes of a four-way propeller under a 2xP excitation are examples of this condition. The vibrating system here consists of the propeller alone and the vibration of the blades cannot be sensed on the propeller shaft or engine mounts.

In the tilt wing or tilt propeller VTOL aircraft, the propeller mounting system may be considerably less rigid and show a greater non-linearity than the mounting of a propeller in a conventional airplane. It is important, therefore, that theoretical procedures be upgraded to account for this flexibility in the determination of the blade (coupled) resonant frequencies for the reasons discussed above. Similar procedures are in use by the helicopter industry for designing rotor blades.

Propeller Whirl Stability

The phenomenon known as propeller whirl flutter is a dynamic instability in which the propeller and its mount experience a diverging whirl-type motion, under the influence of aerodynamic loads on the propeller.

This phenomenon was recognized and investigated in 1938 (J. Aero. S.) by Taylor and Browne, but until very recently the design characteristics of aircraft did not indicate the possibility of this type of flutter and further investigation of this phenomenon was considered of academic interest. Some contemporary propeller driven aircraft have been found to embody design stiffness and damping combinations which could make whirl flutter possible, and therefore it has received fairly thorough investigation recently, in the papers in 1961, by Reed and Bland (NASA TN D-659) and in 1962, by Houbolt and Reed (J. Aero. S.).

The whirl flutter motion is well described in the above papers; the unstable motion is in what is known as the backward precision mode of the propeller and its mounting. In this motion the propeller center

moves in an ever larger elliptical path, in a direction opposite to the direction of propeller rotation. The frequency of this motion is, of course, much lower than propeller rotation frequency. The yawing and pitching motion of the propeller as its center travels in the path described above are a result of the elastic and mass properties of the propeller and its mounting and the gyroscopic and aerodynamic effects of the propeller. In the above papers whirl flutter is studied for a propeller in conventional operation, namely level cruise flight. The aerodynamic forces in the propeller are based on the assumptions that the propeller yaw or pitch amplitude remains small, and that only the quasi-steady aerodynamic effects are of importance. The non-steady or "aerodynamic lag" effects were shown to be small or conservatively negligible. The propeller is assumed rigid, and various combinations of nacelle length, yaw and pitch stiffness, and mass and damping properties were studied, and the effects on whirl flutter were noted in these papers.

The characteristics of certain VTOL aircraft are such that the possibility of whirl flutter developing should be carefully studied. The work of these authors represents a good coverage of the propeller in its conventional mode of operation, but these analyses should be elaborated before applying to the more conventional VTOL configurations. These elaborations might most profitably concern the unsteady aerodynamic effects, the effects of blade flexibility, the possible combined effects of propeller and wing aeroelastic phenomena, and large shaft angle operation, in which the propeller induced velocities are of significance.

6. Airframe Design Dynamic Loads

There appears to be a very real need for a flight loads specification that is specifically tailored to V/STOL aircraft. Nearly all available specifications are formulated on the basis of service experience accumulated by some using agency. Of necessity then, the criteria incorporated in these specifications have been obtained with conventional fixed-wing or conventional helicopter type aircraft. The general configuration

and handling characteristics of these conventional types are nominally similar within their own category, thereby allowing design criteria to be based on a few significant variables since the remaining variables are quite similar (or representative) among these aircraft.

High-speed V/STOL aircraft, however, often possess characteristics significantly different from the conventional types and logically should not be designed upon flight loads specifications generated from conventional aircraft experience. To do so does not necessarily assure a V/STOL aircraft designer that his vehicle will possess the acceptability and integrity that specification compliance would normally insure.

As one example, consider vertical tail flight loads. An insight can be gained into this topic by comparing the design criteria presented in CAM 4b and MIL-A-8861 (ASG) for the cruise configuration. In general, CAM 4b establishes vertical tail loads based on steady-state airplane attitudes resulting from the application of a 300 lb. pedal force from minimum control speed to maneuver speed. Also, CAM 4b gives no direct specification governing the bank angle allowable during these maneuvers.

In contrast, MIL-A-8861 (ASG) treats the transient load condition; that is, loads are determined at the "overshoot" points. Also, this specification applies different pedal forces from CAM 4b at selected flight conditions and flight speeds. Bank attitude during these maneuvers is clearly specified in MIL-A-8861 (ASG) as contrasted to CAM 4b. Generally, should no limit exist for aileron power to control bank angle, the military specification will yield higher vertical tail loads than CAM 4b.

Obviously, the service experience accumulated and incorporated into CAM 4b and MIL-A-8861 (ASG) yields different criteria and different loads when applied to a conventional aircraft type. In consideration of the fact that the lateral damping and side force derivatives of a V/STOL are generally much larger than those of a conventional type, one would expect significantly different lateral dynamics and flight loads.

It becomes important, then, to provide a flight loads specification appropriate to the operation of high-speed V/STOL machines. Proper account must be made of the pedal force-speed-configuration variables in the light of operational mode in order to provide flight loads criteria which would give the designer a reasonably good assurance that specification compliance will provide satisfactory high-speed V/STOL airplane.

APPENDIX

DYNAMIC LOAD PROBLEMS ASSOCIATED WITH V/STOL AIRCRAFT

With reference to item 1 in the Outline of Problems, the following is presented as a brief history of the analysis activity at the Curtiss Division, Curtiss-Wright Corporation on propeller blade first-order (1xP) dynamic loading.

Toward the end of World War II and the period immediately following (early 1946) it became apparent to propeller designers that the first-order or 1xP stresses on propeller blades were becoming of such a magnitude as to cause concern for the fatigue life of the blade and blade retention systems. It was therefore necessary to develop means of predicting this type of loading which would permit the designer to allow for this effect on a rational basis. A theoretical program was initiated concurrently with an experimental program utilizing a specially instrumented C-54 in 1947. Considerable testing was accomplished and correlation showed that this 1xP blade loading was attributable to angularity of the airflow into the propeller disk. A relatively simple analysis resulted in the equation for predicting the magnitude and distribution of the first-order forces.

Consider an airplane flying at such an attitude that the free-stream velocity is entering the propeller disk at some angle, A, then the velocity components at the propeller disk will be as shown in Figure 1.

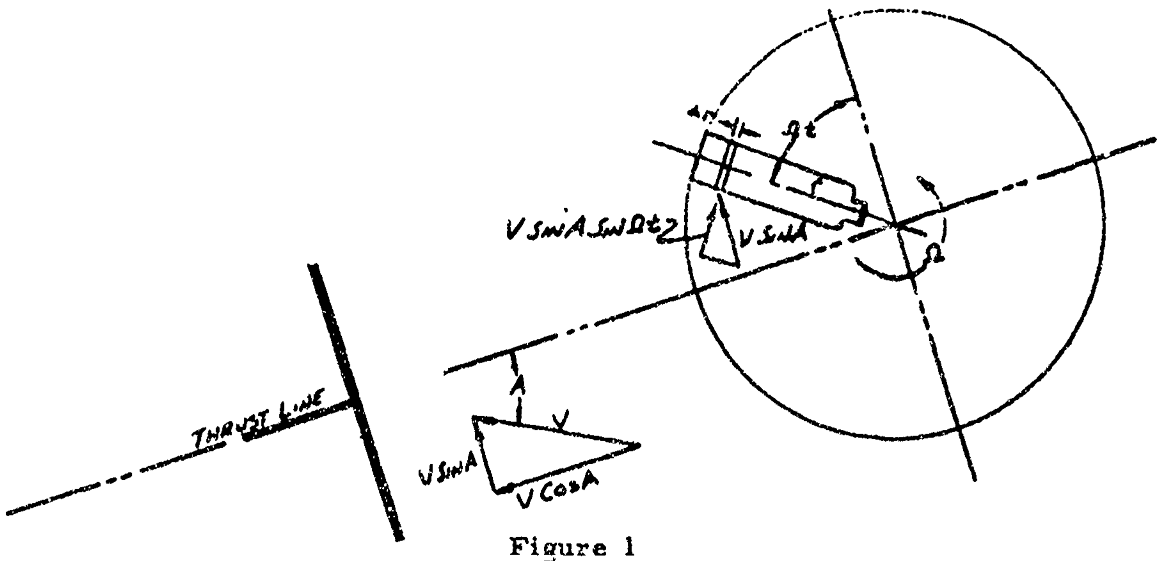

Figure 1

Consider a blade element at radius r, the velocity components acting on this element are:

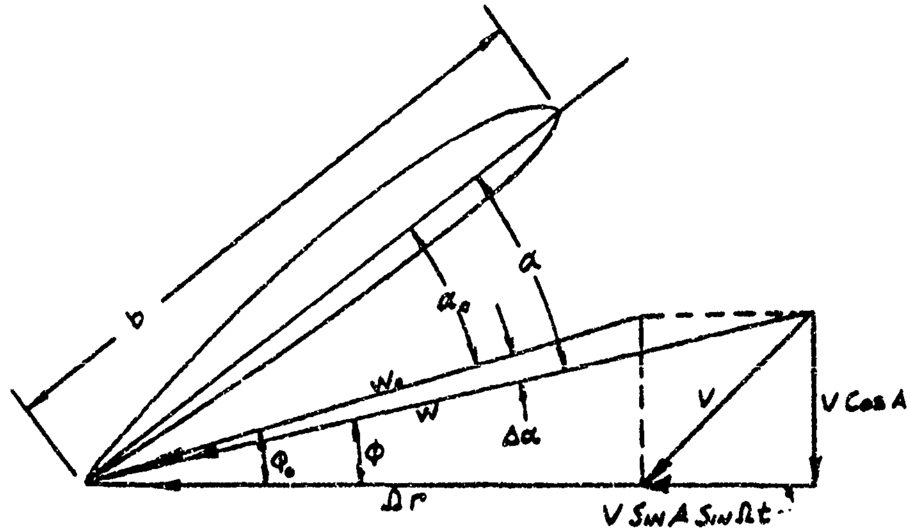

Figure 2

For illustrative purposes the vectors in these figures have been highly exaggerated.

From this it is obvious that the angle-of-attack α will vary with the azimuth angle Ω t.

The lift on this section at any instant will be:

$$\Delta L = \frac{1}{2} \rho W^2 \quad a \; \alpha \; b \; \Delta \; r \tag{1}$$

$$W^2 = V^2 \mathrm{Cos}^2 A + \Omega^2 r^2 + 2\,\Omega r V \mathrm{Sin}\,A\,\mathrm{Sin}\,\Omega\, t + V^2 \mathrm{Sin}^2 A\,\mathrm{Sin}^2 \Omega\, t \tag{2}$$

$$\alpha = \alpha_0 + \Delta\alpha \tag{3}$$

$$\Delta\alpha = \frac{V\,\mathrm{Sin}\,A\;\mathrm{Sin}\,\Omega\,t\;\mathrm{Sin}\,\phi_0}{W} \tag{4}$$

Substituting (2), (3) and (4) into (1) and eliminating steady and secondary terms, it is easily shown that the first order component of lift is:

$$\Delta L_{1xP} = \frac{q \text{ Sin } 2A}{2} \left[ab + 2bC_L \text{ Cot } \phi_o \right] \Delta r \qquad (5)$$

and for the usual magnitude of A typical of conventional aircraft this can be simplified to:

$$\Delta L_{1xP} = Aq \left[a\ b + 2\ b\ C_L \text{ Cot } \phi_o \right] \Delta r \qquad (6)$$

and the total blade forces and moments are obtained by integrating along the blade. It was also noted that when these blade forces were combined at the propeller center line a force and moment, the so-called "1xP couple" and "side force," were produced on the propeller supporting structure, and these were fixed in space on propellers with three or more blades. Considering a pitch-up attitude, the force vector will act to increase lift, and the couple will give a left yaw with a right hand propeller.

With the rapid advance of airplane gross weight, speed, horsepower, and propeller size that followed World War II, these first-order blade loads became a predominant factor in propeller design, the side force and 1xP couple became significant in engine shaft design, and also influenced the aircraft stability.

Obviously, initial attempts to correlate the test data with analytical results using equation (6) left something to be desired and empirical constants were used to force correlation. However, the natural evolution of analytical developments, such as the more refined procedures of aerodynamic analyses which give more accurate values of propeller section operating lift coefficients, lift curve slope, and inflow angles and the more sophisticated methods of blade dynamic analysis significantly improved the prediction of the blade 1xP loading. A major problem was and still is the prediction of the velocity inflow angle at the propeller disk. This is considerably more involved than the airplane angle-of-attack and involves such factors as: wing circulation, flow around the fuselage and nacelles, thrust line orientation, and structural deflection of the propeller supporting structure, influence of high lift devices, etc. The most ideal way to evaluate the flow pattern is by harmonic analysis

of flow patterns taken from a wind tunnel model, and in cases where this has been possible, correlation has been excellent. For the most part, however, such data has not been available in sufficient detail, and the inflow has had to be estimated on the basis of aerodynamic and structural data supplied by the airframe manufacturer and using experience factors to allow for undeterminable quantities.

Over the past 10-15 years the established methods of estimating A and the use of equation (6) has given an entirely satisfactory evaluation of the first-order (1xP) blade loads and stresses both in magnitude and distribution on such aircraft as the 649, 749 and 1049 Connies, C-124, C-130A, C-133, etc. It might also be noted that on conventional aircraft, the propeller loads due to higher harmonic excitation (2xP, 3xP, etc.) are insignificant, unless the propeller is operating in the proximity of a resonant speed, and therefore except for locating resonance points away from operating speeds these higher harmonics were of little concern to the propeller designer.

In the middle 1950's this company became interested in VTOL type vehicles and it became apparent that the simple equations such as (5) and (6) were inadequate at inflow angles in excess of the 20° - 30° range. Further, there was evidence that at high angles the higher orders 2xP, 3xP and 4xP might become significant. The need for a more general procedure for determining blade loading was realized which would provide both the first and the higher order components. Such a general development was initiated under Air Force contract and is reported in WADC TR-58-371.

In essence, this work added to the velocity vectors of Figure 2 an inflow component computed by momentum theory. However, unsymmetrical characteristics were incorporated into this flow pattern based on a study of flow pattern determined on helicopter rotors and reported in various NACA reports. The velocity vectors of Figure 2 now becomes (Figure 3)

For illustrative purposes the vectors in this figure are highly exaggerated.

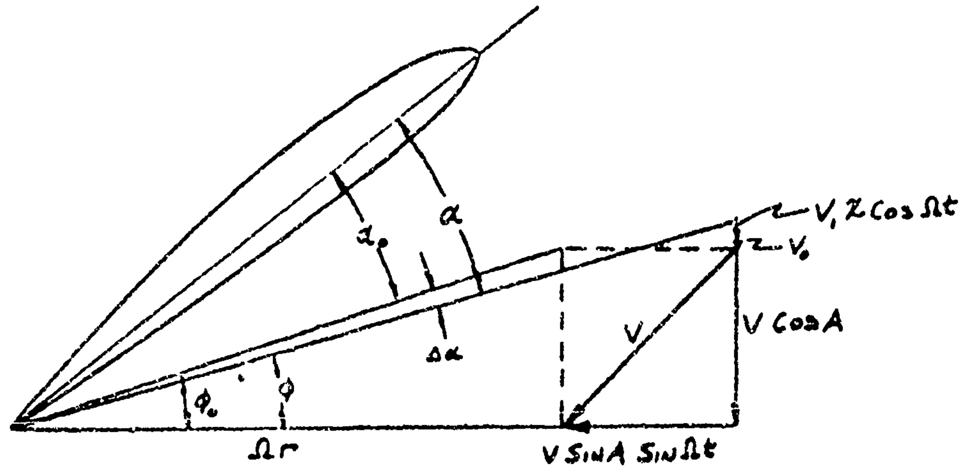

Figure 3

where V_o is a symmetrical or average inflow velocity and can be determined from momentum theory and $V_1 \times \cos \Omega t$ is a correction component to produce an asymmetrical flow through the disk. Again from helicopter and other studies it was found that V_1 was a function of both angle A and the velocity ratio $V \sin A / \Omega R$ where A is the thrust line angle-of-attack.

If the data of Figure 3 are now substituted into the basic lift equation, equation (1), the 1xP load components are considerably more involved than given by equations (5) and (6) and expressions are also obtained for the higher harmonics. In general the load components for the various harmonics can be represented as:

$$*\Delta L_{\eta x P} = \left\{ [\quad] \sin \eta \Omega t + [\quad] \cos \eta \Omega t \right\} \Delta r \tag{7}$$

*For purposes of this paper [ ] represents several terms involving velocity vectors, section aerodynamic characteristics, etc., which are included in the computer program for evaluating these load components.

When the 1xP terms are integrated over the entire propeller it will be seen that for a normal pitch-up attitude the [ ] Sin Ωt terms produce a shaft force in the lift direction and a 1xP couple tending to yaw the aircraft. Likewise the [ ] Cos Ωt terms will give a yawing force and a pitch-up moment. During transition these forces are high and significantly effect the stability and control of the aircraft. These shaft moments vary approximately as shown in Figure 4.

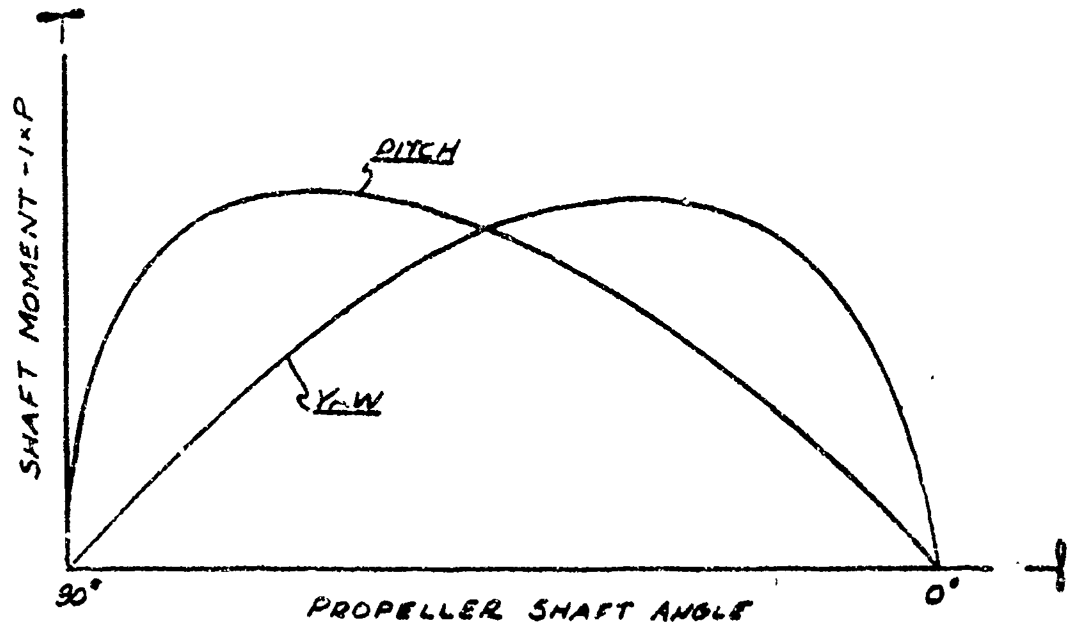

Figure 4

It was interesting to note that for small angles A the 1xP loading of the form of equation (7) reduced to the essentially same value as given by equation (5).

The 1xP component of this expanded loading was correlated against propeller test data subsequently reported in NASA TN D-318. These results showed a good correlation (within ± 15%) at low propeller angles of attack, say below 30 degrees, as expected and at angles above about 75°, but between these limits the agreement requires improvement. It was also found in some cases that while the resultant propeller loads were in acceptable agreement, the predicted blade stresses did not agree too well

with measured stresses which could indicate discrepancies in the distribution of blade loading. The higher order components predicted by the development were small and as yet there has been no correlation with test.

The development of WADC TR-58-371, while a significant improvement over previous work, left much to be desired in the intermediate propeller angle of attack range and it is still necessary to resort to empirical factors to force correlation. To date this correlation factor has been based on free propeller data of D-318 and wind tunnel studies of the Curtiss X-100 and Curtiss X-19 aircraft and is therefore based on total propeller forces as felt by the aircraft, but there is still some doubt as to the accuracy of the blade load distribution, and the accuracy of higher order components of loading.

It is realized that the basic development of 58-371 requires expansion to be generally applicable to the tilting propeller VTOL vehicle. A first step in this direction has been initiated. Basic propeller and rotor flow studies have been restudied and a more complex velocity distribution applied, from which total loads have been computed and the various components separated by harmonic analysis. Correlation with TN D-318 shows a significant improvement for the free propeller case. A more extensive correlation is currently scheduled utilizing test data recently completed in the Ames 40 x 80 tunnel on the X-100 airplane from which it is hoped to obtain data on the effect of wing and fuselage flow patterns.

What is most needed is the development of more precise expressions for the velocity distribution through the propeller disk. With a well defined flow picture it will be possible to accurately predict blade and shaft loads in both magnitude and distribution.

SYMBOLS

A	Angle of attack of airplane thrust line with respect to the free-stream velocity - degrees
a	Slope of the propeller blade section lift curve ($dC_L/d\ \ $)
b	Blade section chord - ft.
C_L	Blade section lift coefficient
L	Section lift - lbs.
q	Dynamic pressure - lbs./ft.^{2}
R	Blade tip radius - ft.
r	Blade section radius, ft.
t	Time, sec.
V	Airplane free-stream velocity, ft. /sec.
V_o	Induced velocity through propeller disk, ft. /sec.
V_1	Modified induced velocity, ft. /sec.
W	Resultant velocity at propeller section, ft. /sec.
W_o	Mean resultant velocity at propeller section, ft. /sec.
x	Proportion propeller radius, r/R
α	Blade section angle of attack
α_o	Mean blade section angle of attack
Ω	Propeller rotational velocity, radians/sec.
η	Multiple order of propeller rpm

V/STOL PANEL

UNRESOLVED DYNAMIC LOADS PROBLEMS ASSOCIATED WITH V/STOL AIRCRAFT OF CONVENTIONAL STRUCTURAL CONFIGURATION

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UNRESOLVED DYNAMIC LOADS PROBLEMS ASSOCIATED WITH V/STOL AIRCRAFT OF CONVENTIONAL STRUCTURAL CONFIGURATION

Charles L. Wharton, Jr.

The Lockheed-Georgia Company is actively engaged in three fundamentally different V/STOL aircraft concepts. The short take-off and landing concept made possible by boundary layer control; the vertical take-off and landing concept made possible by the ejector principle; and the vertical take-off and landing concept made possible by vertical lift engines. Prototype models utilizing the first two of these three concepts have been built and have flown, the USAF sponsored BLC-C-130, a STOL airplane and the Army sponsored Hummingbird or XV-4A, a VTOL airplane.

One basic concept is common to all of these aircraft —— they have conventional type aircraft structure, in conventional configuration consisting of wings, fuselage, empennage, and landing gear as are commonly known. As such, all of these airplanes have dynamic loads problems ordinarily encountered with conventional aircraft and the associated, accepted solutions. These problems include flutter considerations, vibration considerations due to buffet or sonic environments, and all types of landing and ground handling dynamic problems.

These aircraft also have the dynamic loads problems associated with the V/STOL operation which arise from either of, or a combination of, two different design considerations. These considerations are:

1. Abnormal operational requirements dictated by the failure of some system or component of the aircraft such as the control system or power plants. This is a very important consideration for this type of aircraft since it is usually operating at maximum performance near the ground, thus allowing very little time for recovery from such a failure before contact with the surface.

2. Normal operations on an irregular and/or discontinuous surface since this type of surface will be utilized for everyday operations.

It is this second aspect of the design considerations that requires the efforts of the entire aircraft industry as well as the governmental agencies and other types of industry for a satisfactory resolution. This area is a design criteria area and as such will affect the design of all V/STOL type aircraft. This area should not be treated by arbitrary specification requirements but instead the requirements should be established after careful evaluation and analysis of the existing data which has already been obtained under Air Force and NASA sponsorship. There are many very powerful analytical tools available for use in this evaluation. These include:

1. Analog computers to analytically reproduce and predict the dynamic loads.
2. Power spectral density analysis for use in the statistical analysis.
3. High speed digital computers for use in calculating loads at a given time.
4. Frequency response analysis for use when the forcing function can be defined.

Operational requirements resulting from system failures and/or terrain roughness can be satisfactorily accounted for by the use of high energy absorption since both require that large amounts of energy be absorbed. Also it is within the realm of possibility to make the solution to one of these problems complementary to the other. That is to consider, from a criteria aspect at least, that the simultaneous occurrence of a system failure and the design terrain roughness is a dual failure and therefore shall not be designed for. With this assumption then the high energy absorption capability should be useable for either emergency operation due to a system failure while operating on some nomially rough terrain or normal operation on some more severe terrain for which it is designed.

As far as the system failure aspect of the problem, criteria have been developed to establish the design parameters. These criteria consider such things as the number of power plants allowed to fail relative to the weight of the vehicle, the altitude from which the aircraft could recover by diving to attain the stall speed, and the altitude above the terrain required for the vehicle to accomplish transition from a forward velocity to the hover condition.

Let us consider then the criteria for the landing surface, which is the primary source of the dynamic loads problems which, as yet, remain unsolved and that affect the V/STOL aircraft under consideration by the Lockheed-Georgia Company. One of the major reasons for the existence of the requirement for V/STOL aircraft is that they can operate in a relatively small area as compared to conventional aircraft. In addition, it is highly desirable if this area does not have to be an improved area. In this respect we should note here a trade-off consideration between vertical take-off and landing aircraft and short take-off and landing aircraft. With respect to surface conditions the VTOL aircraft has a distinct advantage over STOL aircraft since the VTOL vehicle can hover and, to some extent at least, inspect and select the landing site before touchdown and in addition the area required for landing is for all practical purposes not much bigger than the aircraft. On the other hand, the STOL aircraft has a distinct advantage from a payload carrying capability since it does not require a vertical thrust to weight ratio of greater than one and therefore less power requirements than the VTOL vehicle relative to its weight. Both types of aircraft are confronted with similar problems when taxiing after they are on the surface.

The criteria for the unimproved field must be developed in order to define the forcing functions to be used in the design of the vehicle and to define how much preparatory work, if any, must be done by ground forces prior to aircraft operations from a particular field. Work in this area can be broken into two main classifications both of which must be recognized in the design of the vehicle.

1. The dynamic response of the entire aircraft to discrete discontinuities, to surface undulations, to surface grade charactertistics and to surface hardness characteristics from a structural strength standpoint.

2. The service life of the vehicle from a repeated load or fatigue standpoint when operating from these fields must be considered.

With regard to the first of these two major classifications, it is obvious that the vehicle with conventional landing gears cannot land on a surface which contains sharp edged discontinuities with a depth equal to half the diameter of the smallest tire nor can it land on a surface which allows the airplane to sink very deep into it. Flight tests, with conventional aircraft, have already shown that large cargo aircraft can operate in sand which will not permit operation of standard military trucks. Flight tests have also shown that today's aircraft cannot operate on some hard surfaces due to discontinuities and undulations which military trucks can operate successfully on. What is the criteria then for these fields? The proposed approach to this problem is to utilize the test data which is available to define analytically, surface discontinuities, undulations, and grade characteristics which will produce dynamic loads similar to the experimental data. It should be pointed out that this dynamic loads problem is not confined to the landing gear and supporting structure only. The wings, empennage, fuselage, and power plants are actually more susceptible to structural problems from operations in this environment than is the gear structure. However, the type of landing gear utilized can very definitely affect the other structural members of the vehicle. This approach then will define a set of design criteria for the types of fields utilized for the experimental data.

The next step would be to define how typical these fields are with respect to anticipated operating conditions and to alter the design criteria accordingly. In the process of this second step such things as the soil characteristics and vehicle flotation qualities must be evaluated. Data for establishing these

criteria must be gathered from many sources both government and civilian. Organizations which heretofore have not been actively teamed with the aircraft industry will be called on to furnish data and development work. The army itself will have to play a very important part in the development of these criteria since they are actually the "customer" for whom these requirements were established. We must realize from the very start of this solution, that a stituation exists that is completely analogous to the gust loads criteria situation 30 years ago. We know the problem exists but we do not know how to define its characteristics. There will be periods of trial and error involved since the characteristics change every time they are encountered but eventually a sufficient criteria will be developed. It only remains then to complete the task.

With regard to the service life of the aircraft — this area, of necessity, cannot be fully evaluated until after the strength criteria is established. However, it is obvious that the structure of the aircraft operating in the aforementioned environment will be heavier than that for aircraft operating from paved surfaces for the same number of landings.

With the problem of establishing what has to be designed for, outlined, it now remains to suggest possible structural design concepts which could be applied to the vehicle to make it feasible for operation within this criteria. In this regard there are several means of providing high energy absorption capability for the vehicle.

There are many types of energy absorption devices which might be utilized in the design of V/STOL aircraft to provide a solution to these problems. In order to be somewhat realistic about the use of these devices some type of evaluation criteria must be established which is in keeping with the over-all concept for the use of the vehicle. We could, relatively fast, develop a device which could absorb the required energy, however, the practicality of utilizing such a device on an aircraft then presents quite a problem. In this light then, let us establish a few simple criteria to use in evaluating the various types of devices. We must consider:

1. The weight of the device, since every pound of structure we put into the airframe means one less pound of payload or fuel that we can carry and one more pound of vertical lift required if we take-off and land vertically.

2. The space requirements of the device, since space utilized for such a device means supporting structure and less volume per unit weight for the payload and/or fuel.

3. The actuation mechanism of the device, since the complexity of the actuation mechanism could produce an unreliable system.

4. The usefulness of the device in normal operations since if it is for emergency use only a weight penalty is accepted during normal operations.

5. The operational feasibility of the device from a maintenance standpoint.

A few of these devices for consideration are as follows:

1. Conventional air-oil strut

   For absorption of large amounts of energy, the stroke and diameter of the gear will be excessively large which results in a weight penalty compared to conventional requirements. Space requirements begin to present a problem and maintenance problems due to the unimproved area environment develop.

2. Liquid spring gear

   This type of gear suffers from essentially the same disadvantages of the air-oil strut with the exception of the size. Preliminary studies have shown that the simultaneous criteria of total energy, maximum load, and necessary stroke cannot be satisfied without an excessive weight penalty.

3. Air Bags, Honeycomb cells, other collapsible devices

   Although this is a very efficient method of absorbing energy, the concept may not be acceptable because of the necessary bulky volume to house this type of device and the time required for deployment. Further, for normal operations the devices are dead weight.

4. Progressive failure of the basic airframe structure

   This concept has probably the greatest potential of any considered thus far but at the present day state-of-the-art

it is extremely difficult to determine the exact behavior of such designs. Testing has indicated that somewhat different failure sequences have occurred on apparently identical complex structures subjected to identical loads. It should also be noted that in utilizing this concept the basic airframe would probably have limited operational capability after the structure has failed and that its use during normal operations is highly questionable.

5. Plastic Deformation of Landing Gear Structure

   The plastic deformation concept differs from the progressive failure concept in that the structure deforms plastically but does not rupture. Plastic deformation will occur to some extent prior to rupture of any metal part and by proper design the amount of deformation to absorb the greatest amount of energy within the physical limitations available may be achieved. Studies have shown that a landing gear designed to yield under a load slightly greater than the maximum design loads would weigh no more than a conventionally designed gear for the same conditions. In addition, as long as the structure does not rupture, the elastic portion of the structure is still available for subsequent use even though the total energy absorption capability has been reduced due to the permanent set resulting from exceeding the design load.

6. Rocket Bottles or Reaction Devices

   This concept suffers from the fact that they are dead weight items and are quite sensitive to proper employment in order to obtain the desired results. They would probably require some type of electronic sensing and actuation device.

Inspection of the above listed methods of absorbing energy indicates that the plastic landing gear deformation concept is one of the most efficient means of absorbing energy. It will yield the greatest increase in safety during the landing and take-off phase with the least penalty in weight and is useable during normal operations on abnormally rough terrain.

Since the fundamental purpose of the landing gear is to protect the primary airframe and its contents, the landing gear is obviously the first item of airplane structure that should be sacrificed to absorb the required energy in the event of a system failure or exceedence of design load due to abnormal terrain features.

These then are the major areas of dynamic loads which the Lockheed-Georgia Company faces today and the general approach that is presently anticipated to bring about their resolution.

V/STOL PANEL

DYNAMIC LOAD PROBLEMS ASSOCIATED WITH V/STOL AIRCRAFT

J.E. Martin

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DYNAMIC LOAD PROBLEMS ASSOCIATED WITH V/STOL AIRCRAFT

J. E. Martin

INTRODUCTION

In the design phase of any aircraft, whether it is a VTOL/STOL or fixed wing aircraft, it is imperative that the analyst as well as the designer be continually aware of weight, cost and schedule. To insure that these parameters are given proper consideration in arriving at design loads, one must start with reasonable design criteria. This must be coupled with analytical methods of sufficient sophistication to insure reasonable initial design values. Then having arrived at the preliminary design, use increased sophistication to insure a satisfactory end article.

It has been my observation that all too often the dynamicist has not established design requirements but rather has checked design dictated by other considerations. Thus, improper consideration of dynamic loads in the optimization of the design has resulted in an over-weight configuration and costly vehicle in terms of materials, time and man hours. This problem exists because adequate analytical tools required for optimization are frequently not available. Since vehicle design is an iterative process it is essential that we have analytical tools that fit each phase of the iteration. The final phase of the iterative procedure is that of insuring an adequate vehicle from a strength point of view prior to first flight. This is accomplished by testing. These tests are two distinct types. The first consists of testing a full scale configuration or its component parts. and

the second is that of constructing and testing dynamically similar models.

Each phase of the design program, that is; design criteria, analysis, and testing must be considered when one discusses the problem of the design of the VTOL or any other aircraft. I would like, therefore, to discuss in some detail the problems that are associated with each phase of the design program for the subject configuration.

DESIGN CRITERIA

Design criteria are presently established by each of the procuring agencies for specific designs. However, no design criteria presently exists specifically for VTOL/STOL aircraft. The present criteria are based primarily on existing specifications for fixed wing aircraft or for rotary wing aircraft, and it is being left to the designer to determine just which specification should be used for a particular condition. Although it is true that many of the specifications apply equally well across the board, there are many areas of design requirements which should be and must be established specifically for VTOL aircraft. I will not attempt to define all of these areas for I am not sure that this is possible at this time. However, there are some notable areas that are sadly in need of definition. Among these areas is that of design requirements for the undercarriage. For example, a rational criteria which would establish

the design sinking speed can and should be established as early as possible. Studies comparable to those sponsored by the BuWeps, with regard to Navy aircraft, are required for the VTOL. Here sinking speed is not considered alone, but rather it must be defined with associated fuselage attitude, and side drift velocities.

In addition to the sinking speed requirements, there are those regarding rough terrain, taxiing, and STOL take-off and landing. (In a recent CVC design study these parameters significantly affected the design because of fatigue considerations.) Another area closely akin to that just mentioned is that of dynamic response both from gust loadings and from landings. Data, presently available, are insufficient to properly assess fatigue requirements of aircraft flying at relatively low levels and at speeds which are anticipated for VTOL vehicles. Moreover, the effect of landing response on components other than that of the main gear must be given consideration equal to that presently given to maneuver loads. It is conceivable that the loads imposed on the fuselage, empennage and wing of the VTOL aircraft during rough field operation will significantly reduce the fatigue life of these aircraft.

ANALYSIS AND ANALYTICAL METHODS

Next let us consider some problems associated with analysis and analytical methods. The first area that I would like to

discuss is that of flutter, particularly, the problems associated with propeller whirl flutter. As Mr. Head stated earlier in this seminar, significant time and effort have gone into consideration of propeller whirl problems. These studies, however, have been based on the analyist's estimate of what the mathematical model of the dynamic system should be, without the benefit of previous experience and little information from the literature to guide them. It is true that models have been and are being tested to substantiate the results of these analyses. However, there is practically no parametric information available on this or similar configurations nor is there any concerted effort to derive such data as far as I know. It is my feeling that time and energy should be expended deriving propeller whirl flutter methods that can be used for initial design purposes as well as final design.

In addition to the propeller driven aircraft there are other VTOL configurations, (e.g., the fan-in wing, lifting jets, deflected slip streams) which may require reassessment of unsteady aerodynamics normally used in flutter analyses.

A third problem is associated with the design of propellers when operating in close proximity of the wing of fuselage. This may result in loading conditions that are not fully understood at this time and for which we are ill equipped with regard to

analytical methods. While this problem exists with fixed wing aircraft, the power requirements of the VTOL have made the problems significantly greater.

Another problem area of importance is that associated with the gearing and shafting. Helicopter manufacturers have been coping with this problem for a number of years. However, VTOL aircraft have made new demands on both gearing and shafting velocities and power requirements that are significantly greater than those presently encountered on helicopters. Analytical techniques which properly consider the environment for shafts, operating on a VTOL aircraft, must be reviewed and evaluated to provide the engineer with data that is sorely needed.

TESTING AND MODELING

The increased complexity of VTOL vehicles has resulted in a corresponding increase in the complexity of the mathematical models used to describe their dynamic characteristics. Solutions to these mathematical models are costly in terms of the time required and certainly tax the ingenuity of our best analytical engineers. It follows, therefore, that a less expensive process to handle these problems may be that of dynamic models. This method has been extensively used by the flutter engineers and to a lesser degree by the steady state aeroelastician. I feel that this procedure can be extended to other areas of dynamics;

for example, that of dynamic response resulting from taxiing, landings, or gust environments. Before such models can be realized, it is essential that some initial research work be undertaken to properly establish the required scale factors and modeling techniques. It is not my intention, however, to imply that modeling is a substitute for analytical methods. Rather, it can be used and should be used to a greater extent than in the past, to augment and supplement analytical techniques.

CONCLUSION

In conclusion, I would like to restate the problems previously mentioned. The first of these is that of design criteria. This lack of proper criteria is a significant handicap that presently exists in the design of VTOL aircraft.

The second general area was the problems associated with analysis and analytical methods. These were: (1) propeller whirl flutter, (2) VTOL applications of unsteady aerodynamics, (3) propeller design, and (4) gearing and shafting.

The final item that I discussed was that of modeling. Although this is not a problem area, I feel that a considerable gain can be made by improving our modeling techniques. Therefore, I would like to again recommend that considerable thought be given to this method of defining and solving dynamic problems.

V/STOL PANEL

TWO XV-5A DYNAMIC LOAD CHARACTERISTICS

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TWO XV-5A DYNAMIC LOAD CHARACTERISTICS

(Panel Paper)

W.R. Morgan

This paper is concerned with two particular dynamic load characteristics pertaining to the XV-5A Lift Fan Flight Research Airplane. The two dynamic load characteristics are quite different in nature; one being associated with the XV-5A wing structure, and the problems associated with designing a wing to be flutter free; and the other being that of a critical speed for the lift fan rotor and subject to excitation by steady state axial forces.

WING CHARACTERISTICS

Not too long ago, it was considered quite detrimental, if not impractical, to incorporate lift fans in wings of aircraft especially where a relatively large cut-out in the wing structure is required. This type of configuration was considered detrimental from the standpoint of providing enough torsional stiffness without undue weight penalty, of the order of 20 to 30 percent of wing weight. Only recently, through studies, has it been determined that such a structural design could be accomplished. Based upon these studies, Figure 1 illustrates such a design which accommodates lift fans and with only a 10 to 15% increase in wing weight.

As in most aircraft design, the wing consists of a front and rear spar. The outer panel of the wing is essentially conventional construction. The inner wing panel makes provisions for mounting the lift fans by providing a cut-out approximately 6' in diameter. The fan mounts in three places as illustrated by Figure 1. It is important to note that except at the three mount points, the wing is free to move in bending relative to the fan especially the outboard wing section. By nature of the construction, i.e., allowing for the fan cut-out, there is a loss in wing torsional stiffness, over that which would be provided in wing construction. As can be deduced from Figure 1, torsional stiffness is provided by differential bending of the front and rear spars plus the amount of stiffness contributed by the inboard panel leading edge box structure. Figure 1 shows the relative equivalent GJ and EI for the wing and an estimate of the GJ for an equivalent wing with conventional skin and rib construction. Figure 1 also shows the node lines for two antisymmetrical vibration modes of the wing. One mode having a natural frequency of 11.7 cps. shows the node line running from just outboard of the main rib at the leading edge to just outboard of the wing fuselage intersection. The other mode of 16.6 cps. shows the node line running somewhat aft of mid-chord and then moving forward in the region of the innermost part of the inner panel. The movement of the node line in the 11.7 cps mode is due to the peculiar structural arrangement, i.e., movement inboard at the trailing edge for what is essentially bending.

Initial flutter studies of the wing were conducted on a passive analog for optimization of the structure. It was found that the nominal wing structure as designed on the basis of strength requirements was satisfactory although flutter was encountered at Mach Numbers greater than limit dive speed. The critical mode of flutter was coupled wing bending - aileron rotation. Rigidly restraining the ailerons produced a stable system, therefore, to avoid extreme weight penalties in trying to stiffen the wing, optimization of aileron mass-balance was studied. It was found that by placing the mass-balance at the aileron tip, and thus decoupling the modes, a stable system resulted.

WING CHARACTERISTICS (Continued)

Since the ratio of bending to torsional frequency is approximately 0.7, it would be believed that the bending mode might be the more critical. As it was seen later, both by the analog studies and by a scaled flutter model, the critical mode of flutter is essentially wing bending coupled with aileron rotation.

Vibration modes with and without fan gyroscopic moments acting were obtained from the same analog setup. Measurements of the modes with gyroscopic forces showed that the phase angles between deflections were generally small (less than 10° except for deflections of very small amplitude). Frequency shifts between the modes with and without gyroscopic moments were very small whereas damping varied on the average by approximately six per cent.

LIFT FAN ROTOR CHARACTERISTICS

Quite some time ago, it was recognized that rotating discs (for example, electric power steam turbine discs) exhibited the phenomena of fatigue failure due to sympathetic vibration as a result of extemporaneous steady state axial force applied to the turbine rotor buckets. As a matter of fact, in the early 1900's disc turbine rotors with peripheral blades were experiencing fatigue failure for no apparent reason. Because of necessity, extensive research was carried out in the case of steam turbine discs to ascertain the reason behind such failures. At that time it was learned that this type of disc rotor can be set into sympathetic vibration by only a few pounds of steady state force applied at the same point as the rotor rotates by this point. Such is the case with the XV-5A lift fan rotor, especially at off design point speeds. This characteristic is illustrated by Figures 2 and 3. Figure 2 shows the fan blades which carry relatively small impulse turbine buckets at the blade tips. The fan blades at the hub are connected through a dovetail to the hub disc.

Gas power energy is received by the turbine buckets through a scroll (also illustrated by Figure 2). Figure 3 schematically illustrates the potential steady state force by force vectors throughout the 180° arc. In terms of the wheel motion, once every revolution, the wheel may be pulsed by an unbalance force. This gives rise to the possibility of a traveling or stationary wave around the periphery of the rotor assembly, depending on the rotor speed. Consistent with the masses and spring rates of the assembly, when the circumfrential velocity of the wave equals, but is opposite in direction to, the rotor peripheral velocity, a standing wave with 2, 4 . . . 2n node points will exist. The rotor speed corresponding to these conditions is the critical speed, ω_c. Schematically, this phenomena is illustrated by Figure 4. Figure 5 pictorially illustrates the same phenomena. Although 2n node vibrations are possible, relatively minor stress problems accompany these possibilities when compared with the fundamental four node vibration, primarily because the driving force required for the higher node vibrations is considerably higher than for the four node vibration.

LIFT FAN ROTOR CHARACTERISTICS (Continued)

During tests of the lift fan rotor, both steady state and vibratory strain gage stresses have been measured. Max stress due to the 4 node vibration occurs at the root of the fan blade (Figure 6). This stress was a cyclic stress superimposed on a steady state stress. From the stress measurements and for a high strength material, a fatigue life of about 10^8 cycles would be obtainable as illustrated by the Goodman diagram (Figure 6). From the strain gage measurements it was determined that the 4 node critical rotor speed is approximately 2050 rpm., compared to a 100% design rotor rpm. of 2640, providing a vibration frequency of 68 cps. The 6 node vibration was also measured at about 1700 rpm with a corresponding frequency of 85 cps. Prior to the testing, predicted critical frequencies were obtained by analytical elastic treatment of the combination disc, fan blades and buckets. The 4 node was predicted within 25 rpm and the 6 node within 100 rpm.

Although the most important stresses for this application arise from wheel critical speeds, there are others that analytically complicate the design problem. These stresses include those from first and higher order fan blade flexural modes, torsional modes, one per rev pulse that occurs during high angles of attack, and high cross flow velocities, advancing and retreating fan blades relative to cross flow velocity, four per rev pulses due to struts ahead of fan blades, and stresses due to gyroscopic loads.

As with most problems of this nature, the question of appropriate combinations of the various stresses is a difficult design decision when coupled with the fact that one should take into account the fact that both mechanical and aerodynamic damping tend to suppress various vibrations. Design approach to date has been that of conservatively combining the various dynamic stresses and taking no credit for mechanical and aerodynamic damping.

Despite the complexity of the stress pattern, rotors of the nature discussed have been built and tested. Around 500 operating hours of test time have been accumulated both during static and cross flow wind tunnel conditions. This test time includes operation in the wheel critical frequency for sustained periods of time.

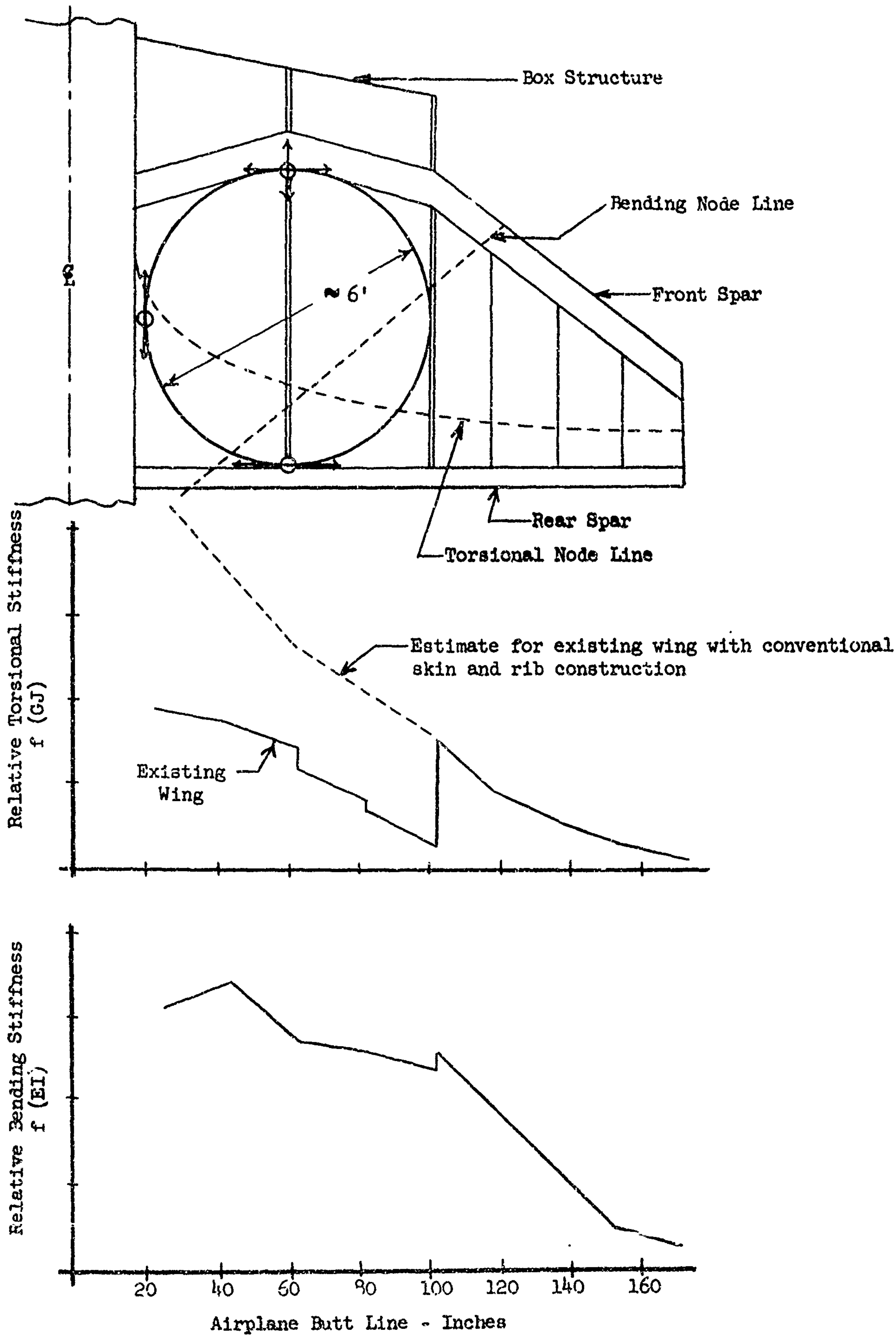
DISCUSSION

The XV-5A wing structure design features should provide one approach to accomplishing inclusion of lift fans in wings and with a wing weight structural penalty of the order of 10 to 15%. By proper design of the aileron from a flutter standpoint, it is felt that flutter can be avoided for this type of structure.

From the structural description and vibration investigation of the wing to date, one possibility of inclusion of lift fans in wings without undue penalties is illustrated. Further study and analysis of this concept might well produce other approaches wherein lift fan and wing are more integrally designed and desirable wing characteristics better optimized.

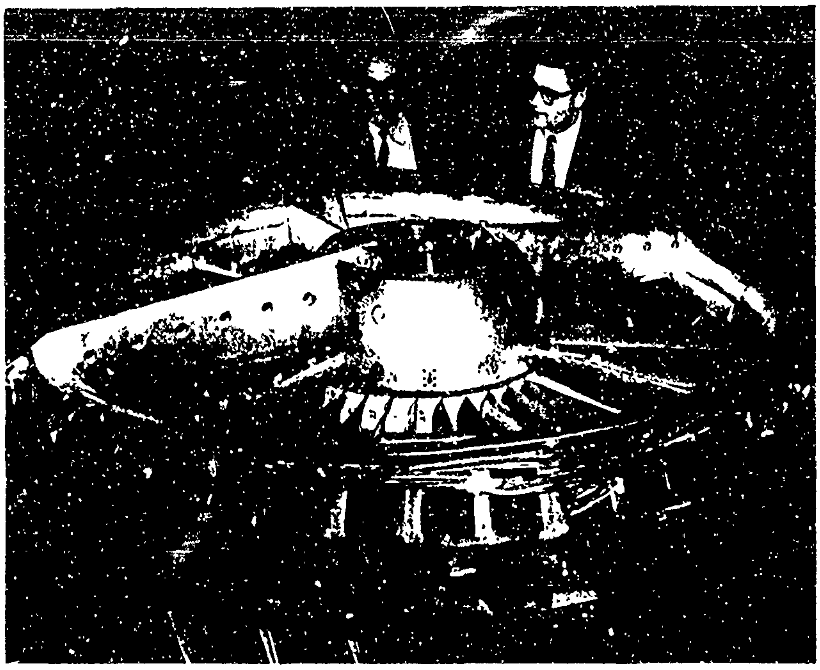
DISCUSSION (Continued)

The response of the XV-5A lift fan rotor to major vibration modes has been predicted and verified by experimental measurement. Stresses arising from the vibrations have been measured in static and wind tunnel tests and have been used to establish safe running limits for the XV-5A test program. By nature of the fan application, the stresses due to the various modes of vibration, suppressed by damping, are difficult to predict precisely. However, through many hours of test, the capability of the rotor to operate throughout the intended range has been satisfactory. Undoubtedly, continued experimentation should provide more insight into refined analysis/design procedures.

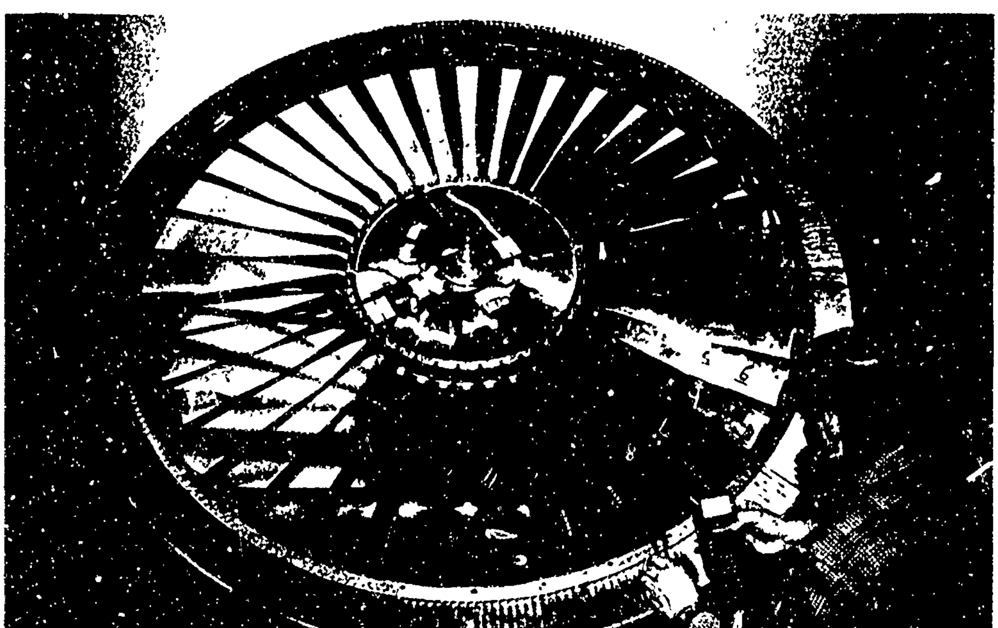


Box Structure
Bending Node Line
Front Spar
≈ 6'
℄
Rear Spar
Torsional Node Line
Relative Torsional Stiffness
f (GJ)
Estimate for existing wing with conventional skin and rib construction
Existing Wing
Relative Bending Stiffness
f (EI)
20
40
60
80
100
120
140
160
Airplane Butt Line - Inches

Figure 1

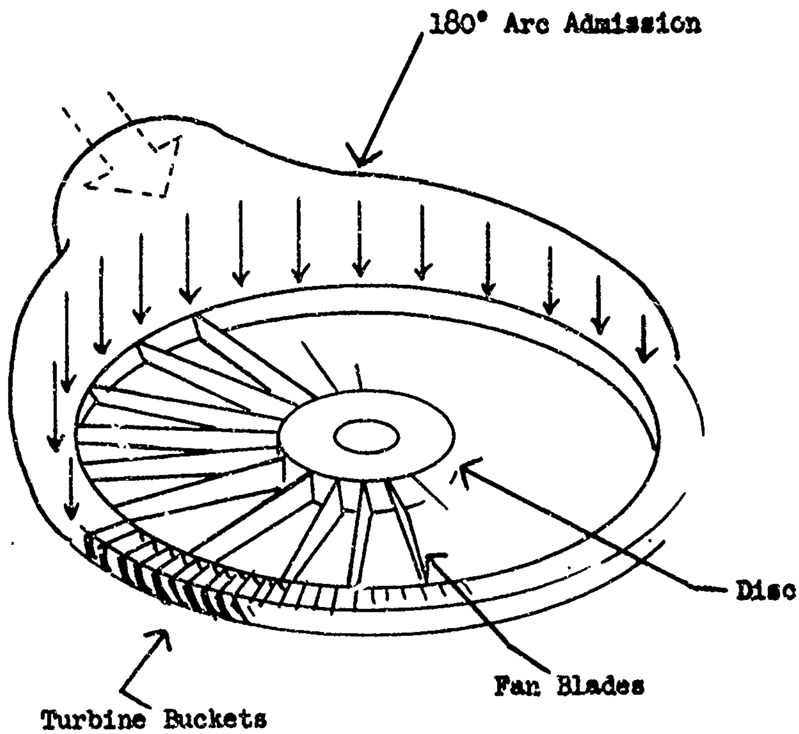


XV-5A Lift Fan Assembly



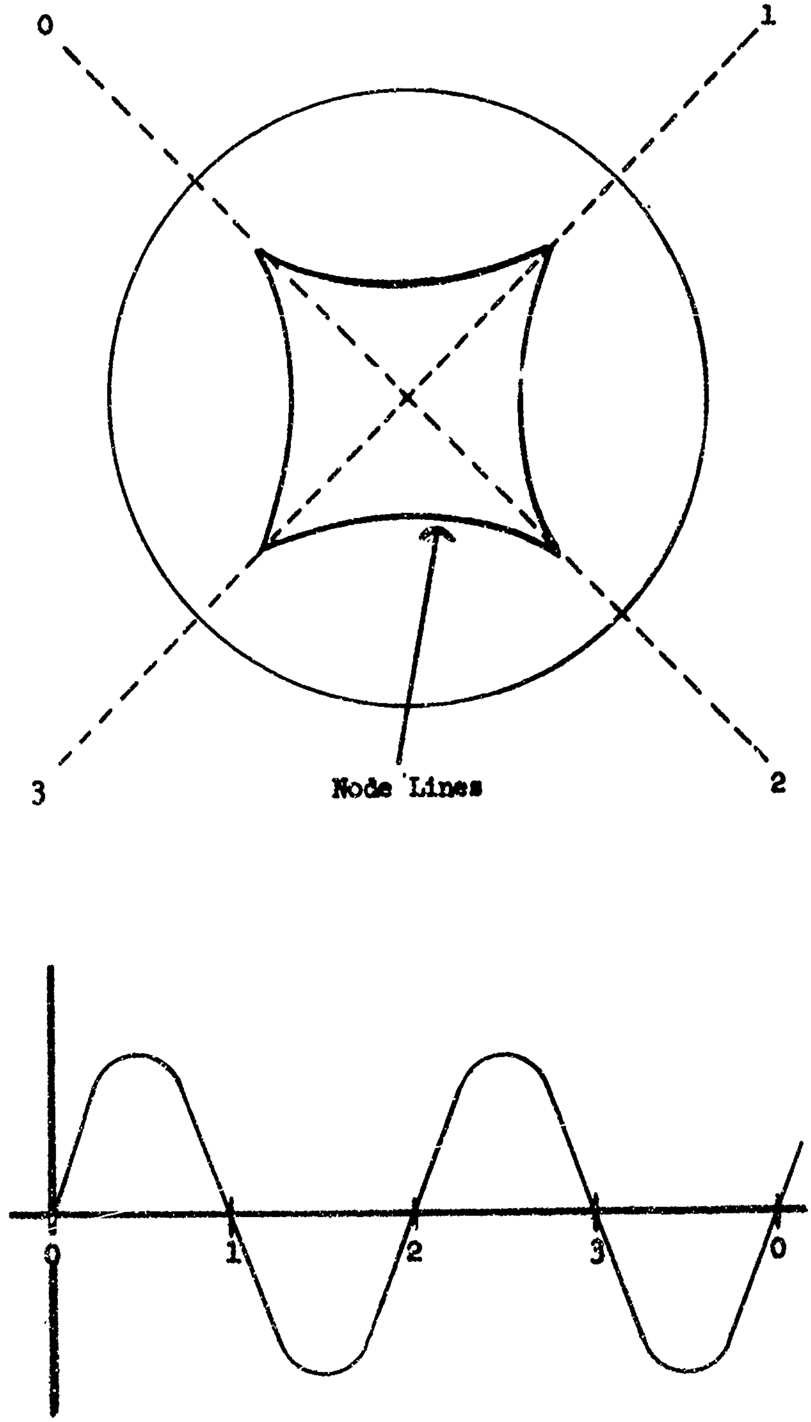
XV-5A Tip Turbine Fan Rotor Assembly

Figure 2.



SCHEMATIC OF BUCKETS, BLADES & DISC

Figure 3



SCHEMATIC OF 4 NODE VIBRATION MODE

Figure 4.

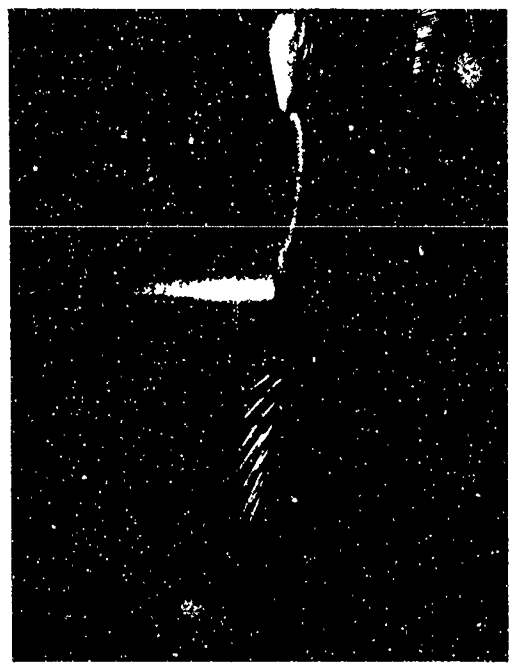
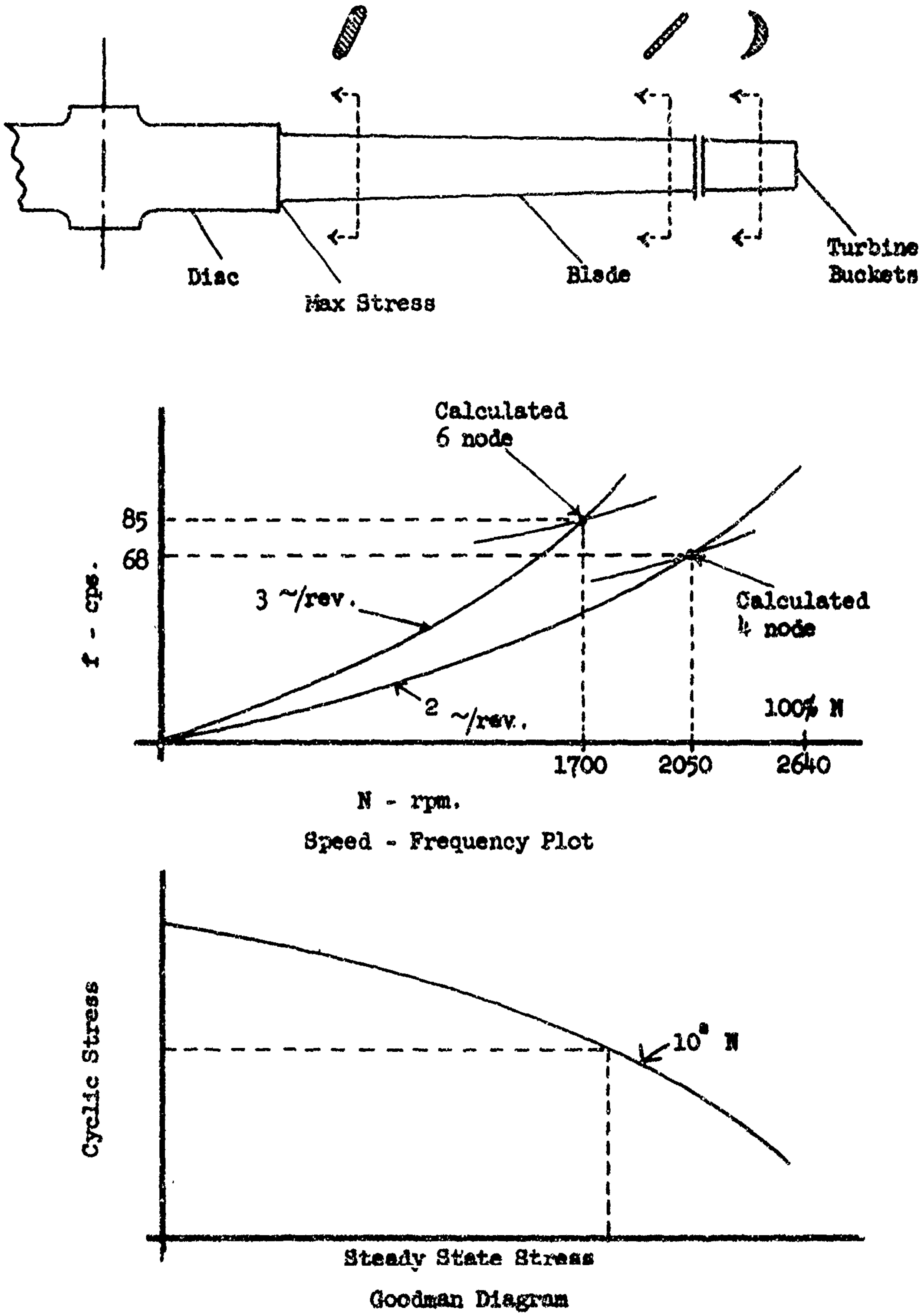


Figure 5. India Rubber Wheel Exhibiting Wave Phenomena



Disc
Max Stress
Blade
Turbine Buckets
Calculated 6 node
85
68
f - cps.
3 ~/rev.
2 ~/rev.
Calculated 4 node
100% N
1700
2050
2640
N - rpm.
Speed - Frequency Plot
Cyclic Stress
10^8 N
Steady State Stress
Goodman Diagram

Figure 6

V/STOL PANEL

DYNAMIC LOAD PROBLEMS OF V/STOL AIRCRAFT

W.H. Buckley

Bell Aerosystems Company

Buffalo, New York

DYNAMIC LOAD PROBLEMS OF V/STOL AIRCRAFT

W.H. Buckley

I. INTRODUCTION

The dynamic load problems of V/STOL aircraft are as varied as the types of V/STOL aircraft now flying or under development. In their broadest aspect they call for the establishment of design criteria which define the applicable performance requirements and set design objectives which will result in safe, useful, and economical aircraft. In their most detailed aspect they call for the solution of dynamic load problems which are particular to the design features and operating environment of individual aircraft. My remarks today will be directed toward a general review of VTOL design criteria problems and a brief discussion of one dynamic load problem of interest for aircraft featuring shrouded propellers.

II. DESIGN CRITERIA

One of the first problems to be considered in establishing V/STOL design criteria as shown in Figure 1 is that of deciding whether existing helicopter or conventional aircraft flight load criteria should serve as a basis for structural design. At the present time, modification of conventional aircraft flight load criteria to cover vertical and transitional flight modes appears to offer a reasonable approach. In particular it is possible to construct V-n diagrams which apply to the various configurations through which the aircraft passes during transition. The question remains, however, as to the load factors, limit airspeeds and types of maneuvers which should be associated with these V-n diagrams.

In regard to landing load criteria, the fact that limit sink speeds are specified in MIL-S-8698(ASG) while design sink speeds are specified in MIL-A-8862(ASG) results in a problem of establishing uniform load criteria. Moreover, the question also exists as to whether the limit sink speeds specified for helicopter design in combination with $\frac{2}{3}$W lift are applicable to the various other types of VTOL aircraft. The formulation of new loading conditions may also be in order because of requirements for STOL operation from unprepared landing sites.

The establishment of repeated load criteria involves each of the above problems as well as others which are particular to operation of V/STOL aircraft. Among these

additional problems are those associated with allocating total flight time between conventional and transitional flight, as well as vertical flight in the case of VTOL aircraft. A parallel problem exists in regard to the allocation of total landings among the various symmetrical and unsymmetrical landings associated with vertical and horizontal landings. Maneuver and gust load factor spectra also require the establishment of transition flight profiles which will be representative of aircraft operational experience. This is especially important for structural components which are highly loaded during transition.

It appears doubtful that criteria can be formulated at this time which are applicable to V/STOL aircraft on a general basis as is now done for helicopters and conventional airplanes. Rather it seems more likely that for some time each V/STOL aircraft will require the establishment of criteria tailored to the design features and performance requirements of the aircraft in question. In the meanwhile, however, it may be worthwhile to first of all attempt to define those areas in which additional load criteria should be formulated for V/STOL aircraft and secondly to summarize the particular load problem areas which are known to be of importance as a result of current operation and design experience.

III. DUCTED PROPELLERS

A particular problem area for VTOL aircraft featuring shrouded propellers is the determination of propeller blade loads and shaft torques at high duct incidence angles and high forward speeds. Wind tunnel tests at NASA-Langley, NASA-Ames and at the University of Wichita have shown that at high duct angles of attack, flow separation can occur over the lower interior sector of the shroud starting at the lip. Because of the asymmetric nature of the stalled airflow, the propeller blades are subject to relatively large increases in local angle of attack as they pass through the low velocity stalled airflow, followed by a return to more normal angles of attack as the blades rotate through the remainder of their 360 degree arc. This flow condition is characterized by a sudden increase in the acoustic output of the duct suggesting a severe blade stressing condition. A limited amount of duct stall data is available from the Langley and Ames wind tunnel tests. The testing at NASA-Langley was performed with a 1.25 foot diameter propeller while that at NASA-Ames was performed with a 4.0 foot diameter propeller corresponding to a full scale duct from the Doak 16 VTOL research airplane.

This data has been found to be of interest to the extent that it may indicate the flight conditions under which a typical ducted propeller airplane might encounter duct stall. One of the limitations of the data is that it did not show in any direct manner the influence of duct thrust loading on the duct stall boundary. Since it was evident from the data that a powered duct could be operated without internal duct stall at angles of attack at which an unpowered duct would certainly stall, the influence of thrust loading was considered to be of importance. In order to extend the available data to a range of thrust loadings, the empirical procedure outlined in Figure 2 was employed. As shown in this figure an apparent angle of attack at the lip was found by the vector addition of the tunnel free stream velocity and in axial flow velocity along the duct center line. The latter was made equal to the sum of the tunnel velocity and one-half of the induced velocity calculated for the test thrust loading using simple momentum theory. This procedure is by no means rigorous, but was intended to determine whether an apparent angle of attack at the duct lip could be found which would remain constant for a variety of duct angles of attack and thrust loading.

The results of this investigation are shown in Figure 3. The data presented in TN D-995 produced an apparent duct angle of attack at the onset of duct stall which was relatively constant, while the data of TN D-1301 showed a larger and more variable angle of attack. The difference in angle of attack has been attributed to the higher Reynold's number associated with the full scale duct employed in the tests at NASA-Ames. The changing angle of attack is attributed to the fact that the empirical procedure employed does not properly account for the inflow velocity at the duct lip.

For purposes of determining the influence of thrust loading on duct stall at a particular angle of attack it has nevertheless been assumed that the apparent angle of attack could be taken as constant over a range of thrust loadings. Based upon this assumption, the data of TN D-1301 was extended to cover a range of disk loadings and compared in Figure 4 to the limit airspeed of a typical design. The airplane angle of attack corresponds approximately to that at which the limit airspeed can be attained under steady flight conditions.

In this figure it appears that the flight condition most likely to encounter duct stall corresponds to attaining maximum airspeed in combination with maximum duct incidence. The influence of a pull-up maneuver under these conditions is indicated in Figure 5 which relates the previous duct stall boundaries to the limit airspeed boundary for an airplane angle of attack of 0 degrees. The likelihood of encountering duct stall at high duct incidence angles is seen to be significantly increased. Also shown in Figure 5 is a duct angle versus airplane velocity conversion schedule corresponding to a take-off transition in which airplane angle of attack is held equal to 0 degrees. Here also the flight conditions most likely to encounter duct stall are associated with high duct incidence angles. In view of the empirical procedures involved in defining the duct stall boundary shown here, it should be noted that no firm conclusion can be drawn as to whether duct stall will or will not occur.

Figure 6 is based upon data taken from NASA TN D-995 and is presented in order to show the changes in propeller thrust and pitching moment which accompany the onset of duct stall. As a result of the stall, the thrust on the propeller is increased while the thrust on the shroud is decreased. In addition, as the thrust on the propeller is increased, a nose up pitching moment is also evident, suggesting an asymmetric loading on the propeller disk resulting from an increase in thrust in the region of the stalled airflow.

Further evidence of the nature of duct stall is given in Figure 7 which is based upon data presented in University of Wichita Engineering Research Report No. 213-17. The shroud employed in this instance featured a relatively sharp leading edge which was susceptible to duct stall. As a result, the velocity profile shown in Figure 7 which is measured behind the propeller disk is considered to reflect a relatively severe stall particularly at 60 degrees angle of attack. In any event, the highly asymmetric velocity profile shown suggests that important dynamic blade loads are likely to be associated with this condition.

Figure 8 is presented to show that blade dynamic load problems may not be confined to duct stall conditions. In this instance the shroud configuration is one which is not particularly susceptible to duct stall. Both the thrust loading and the duct angle of attack are high for the condition shown. The upper half of the figure shows the pressure rise across the propeller disk measured at the wall of the shroud. It is apparent from this figure that the pressure rise varies substantially from point to point around the shroud and suggests that substantial blade dynamic loads may be involved.

While the foregoing data has no quantitative significance other than for the particular ducts which were tested, it nevertheless indicates that in determining propeller blade dynamic loadings, internal duct airflow during flight at high duct incidence angles will be a major consideration.

IV. CONCLUSION

Only two aspects of the dynamic load problems associated with V/STOL aircraft have been discussed here, namely, the general problem of establishing structural design requirements for V/STOL aircraft and the more detailed problem of nonuniform airflow associated with shrouded propellers. This is not intended to imply that other problems do not exist or that these are of overwhelming importance. They are instead problems that are of interest in the design of a typical ducted propeller aircraft.

FLIGHT LOAD CRITERIA

(A) MIL-A-8861 (ASG) OR MIL-S-8698 (ASG)
(B) TRANSITION LIMIT AIRSPEEDS
(C) TRANSITION LOAD FACTORS
(D) TRANSITION MANEUVERS

GROUND LOAD CRITERIA

(A) DESIGN SINK SPEEDS VS LIMIT SINK SPEEDS
(B) SINK SPEEDS AND LIFT ACTING FOR VERTICAL LANDINGS
(C) STO LANDING AND TAKE-OFF LOADING CONDITIONS

REPEATED LOAD CRITERIA

(A) ALLOCATION OF FLIGHT TIME TO VERTICAL TRANSITIONAL, AND CONVENTIONAL FLIGHT
(B) ALLOCATION OF NUMBER OF LANDING TO VERTICAL AND CONVENTIONAL LANDINGS
(C) TRANSITION, GUST AND MANEUVER LOAD FACTOR SPECTRA

FIGURE I. V/STOL LOAD CRITERIA PROBLEM AREAS

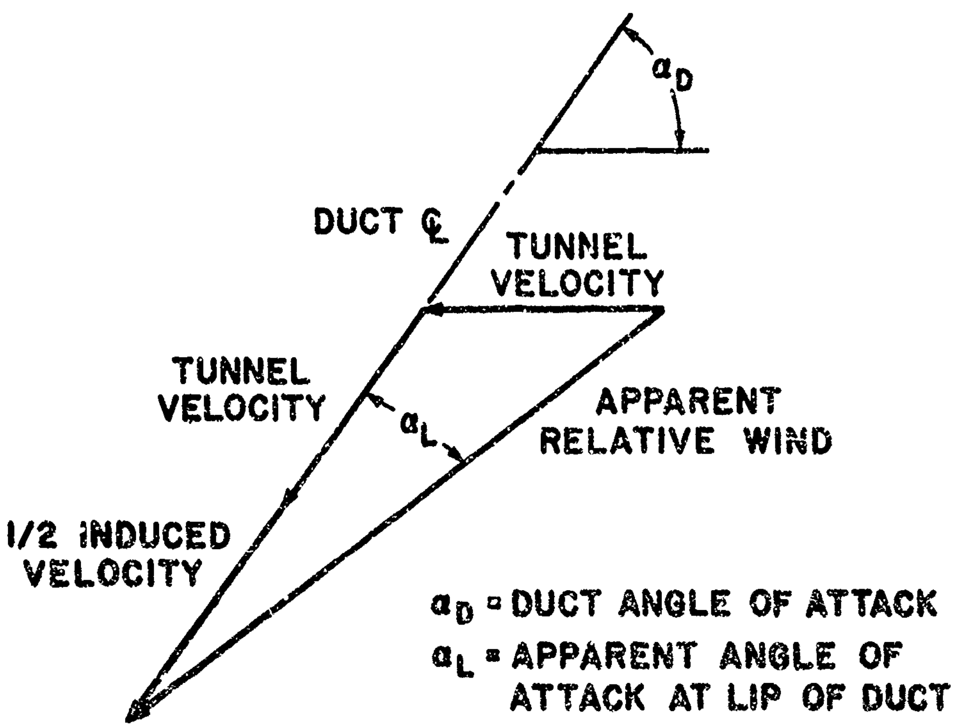


FIGURE 2 EMPIRICAL DETERMINATION OF LIP ANGLE OF ATTACK AT THE ONSET OF DUCT STALL

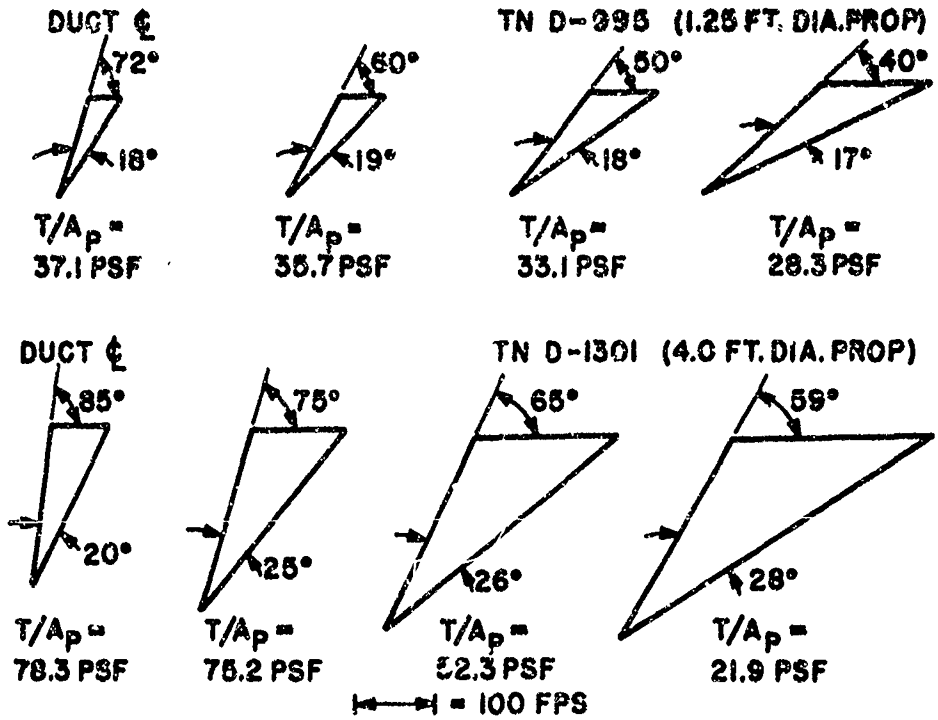


FIGURE 3 APPARENT DUCT ANGLE OF ATTACK AT ONSET OF DUCT STALL

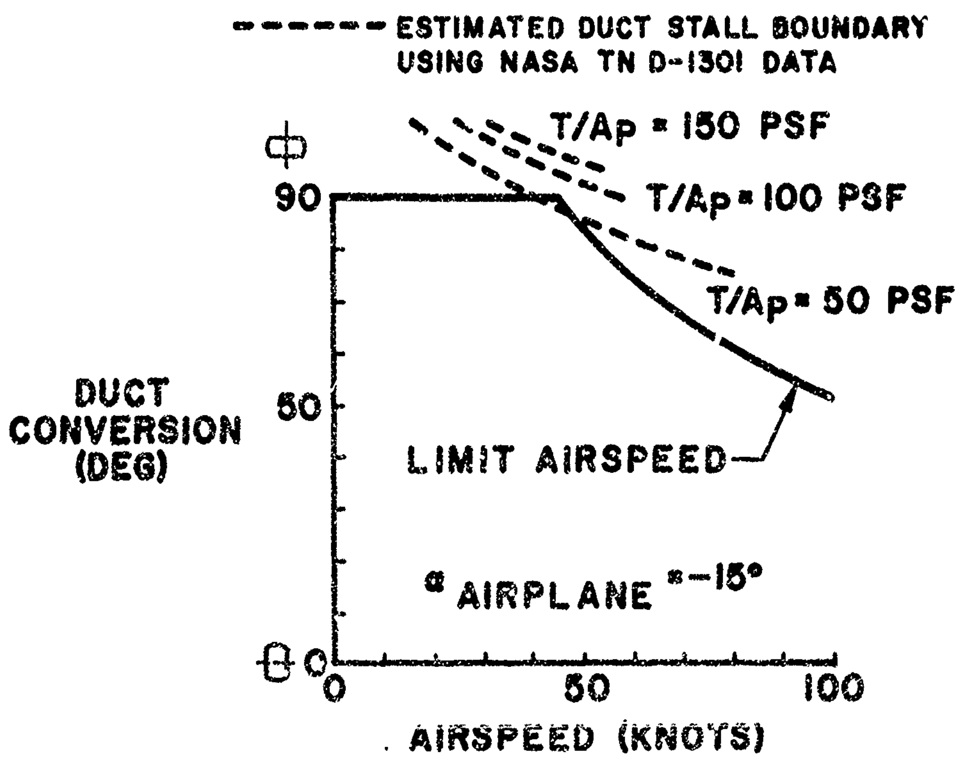


FIGURE 4 ESTIMATED DUCT STALL BOUNDARY: α = -15°

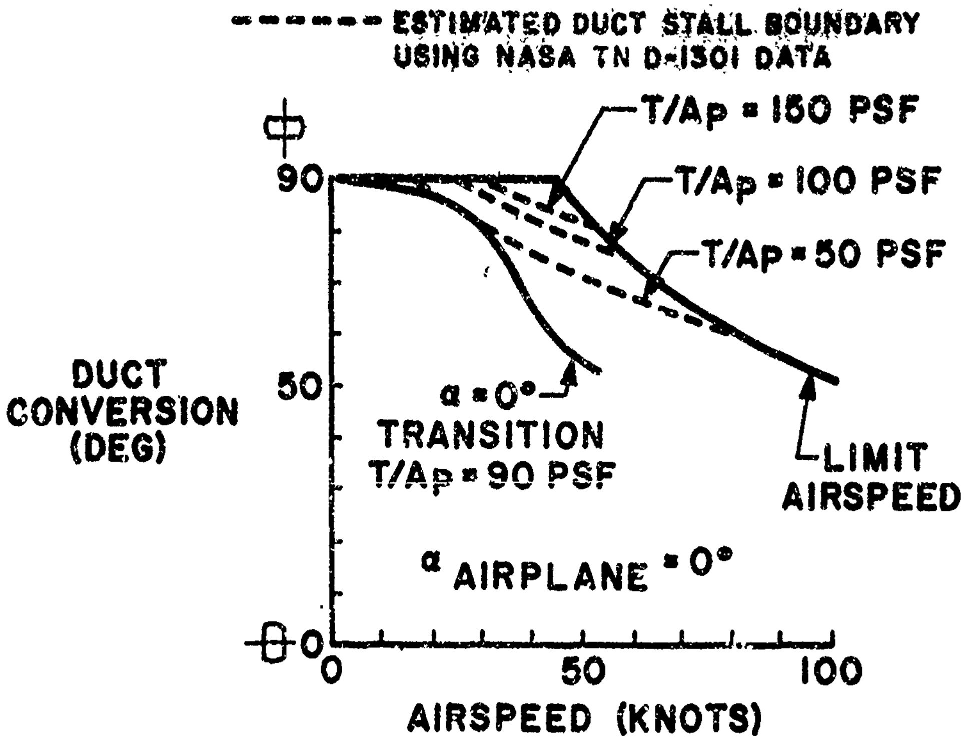


FIGURE 5 ESTIMATED DUCT STALL BOUNDARY: α = 0°

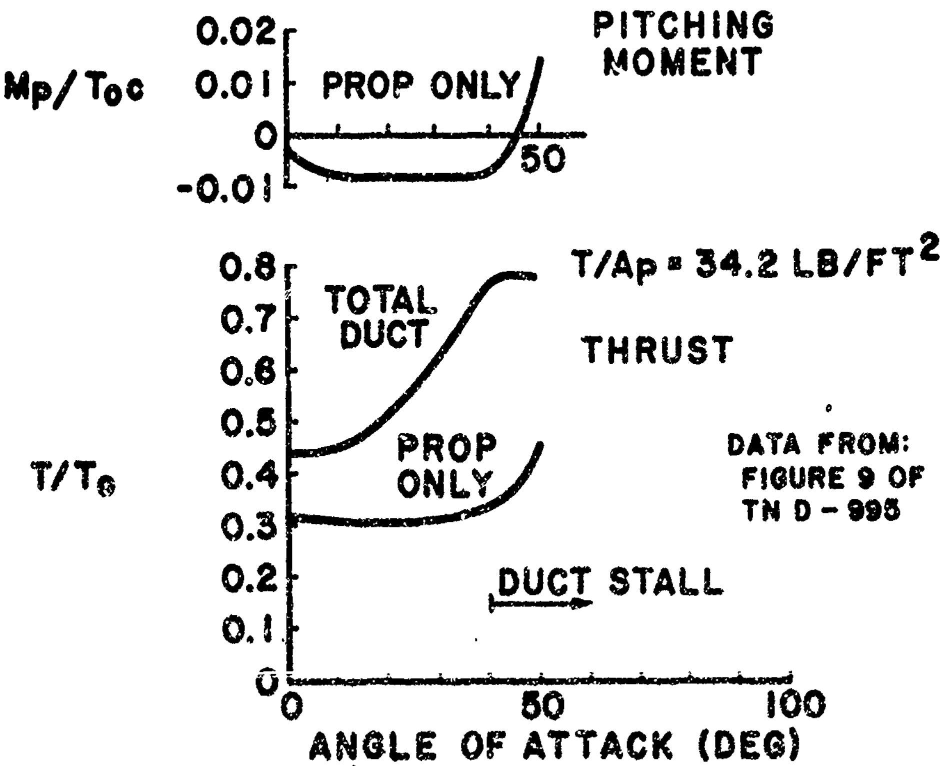


FIGURE 6 PROPELLER FORCES AT DUCT STALL

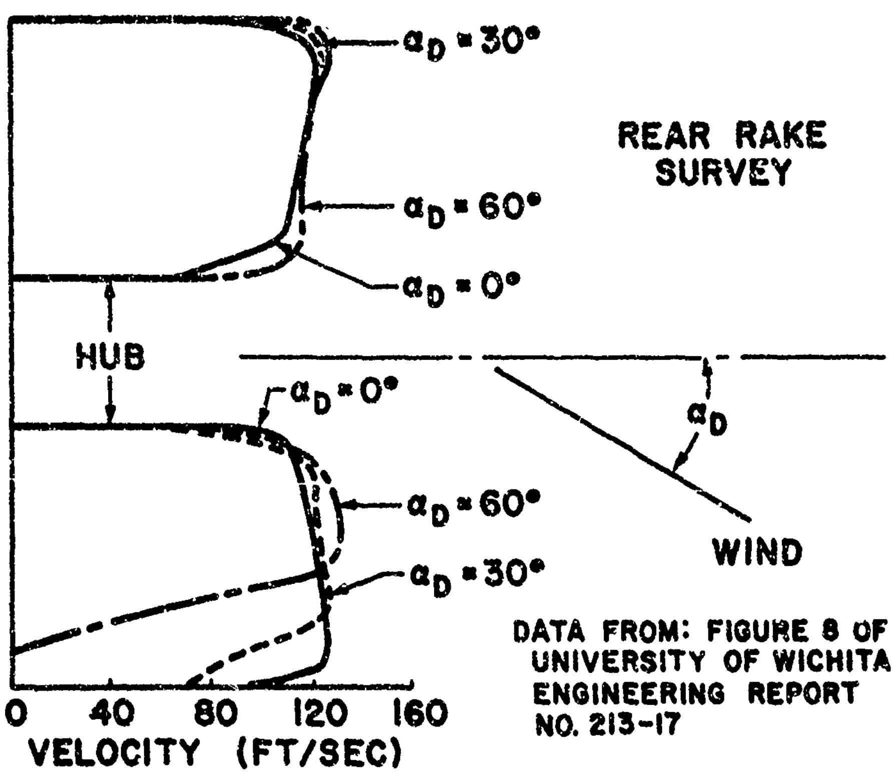


FIGURE 7 SHROUDED PROPELLER VELOCITY SURVEY

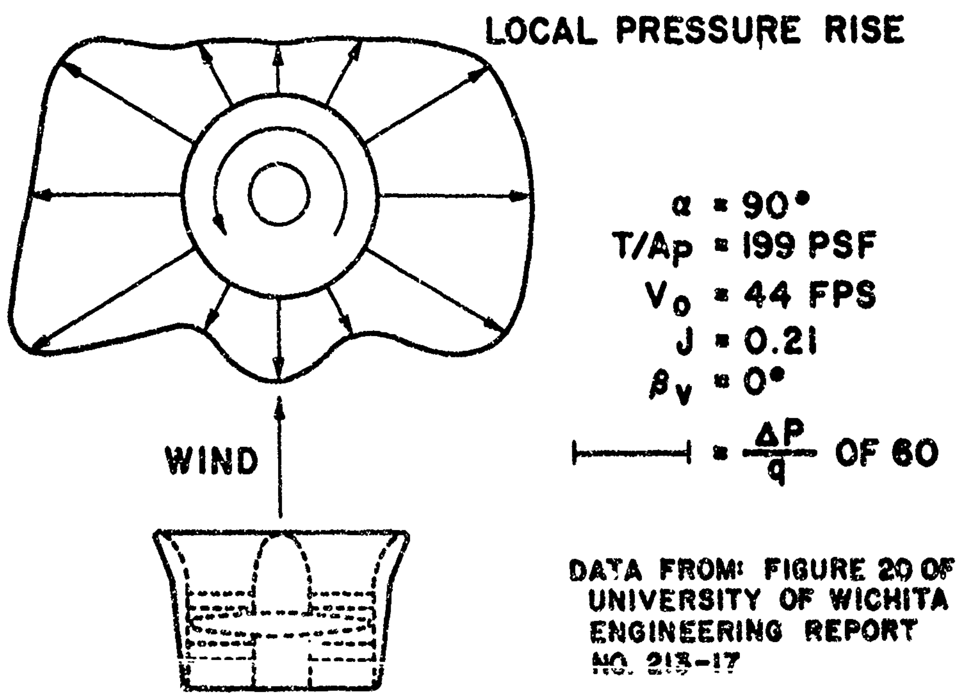


FIGURE 8 PRESSURE RISE ACROSS PROPELLER DISK MEASURED AT WALL OF SHROUD

AREAS OF FUTURE RESEARCH RECOMMENDED BY THE HELICOPTER PANEL

AREAS OF FUTURE RESEARCH RECOMMENDED BY THE HELICOPTER PANEL

The panel review of the prepared presentations and of the audience's comments results in the following recommendations which were concurred in by all members of the panel.

Recommended Areas for Future Research

1. It is recommended that flight load surveys under field conditions be continued. Measurements of airspeed, altitude, normal force, gross weight, power, etc. should be obtained simultaneously. Data should be obtained for several types of aircraft during actual service missions. The results should be correlated with existing data and an attempt should be made to extrapolate the results to additional flight profiles. An agency should be assigned the data analysis responsibility.

2. New techniques should be developed for the fatigue life substantiation of dynamic components. Military qualification specifications should then be reviewed for possible modification.

3. It is recommended that manufacturing techniques and instrumentation methods for models be investigated to allow more extensive use of such models for investigating the gross effects of rotor blade, twist, planform, size, stiffness, mass distribution, etc. Full scale rotor tests should be continued for speeds and flight conditions beyond present flight envelopes.

4. It is recommended that data be obtained on airfoils in current use for the proper range of Reynolds numbers and for extended Mach number ranges. Data should be obtained for various blade skew angles and through an angle-of-attack range of 180°. The effect on blade section characteristics due to oscillatory angles-of-attack should also be investigated. The search for new rotor airfoil sections should be reinstigated with a goal of increasing the drag divergence Mach number while at the same time maintaining high stall angles and low moment variations.

5. Recommend, development of improved methods for predicting control loads, vibratory shaft loads, and related fuselage vibration. Current indications are that this group of problems must be more accurately predicted to allow the satisfactory operation of helicopters in the higher speed regimes. Comprehensive tests and analyses on rotors representative of current industrial designs should be conducted in the near future to provide information applicable to advanced helicopter designs.

6. Considerable progress is being made in the analytical prediction of rotor induced velocities. This program needs to be continued to allow definition of the relative importance of the various parameters involved; and allow the establishment of an adequate engineering method for determining rotor inflow. Such methods would allow rapid prediction of high speed performance, vibratory loads and rotor dynamic characteristics.

7. Present supercritical shafting research should be extended to allow the prediction of support response as a function of damping, shaft speed and shaft unbalance. Work should be initiated to define shaft unbalance. level as a function of shaft total indicated reading (TIR) and its distribution along the shaft; and further, present studies should be extended to fully investigate the shafting critical speed phenomena as a "whirling" instability rather than a lateral vibration problem. Additionally, the scope of the studies should be expanded to define "equivalent" viscous damping of various possible damping materials, such as rubber, friction material, etc.

8. Mathematical models presently used to represent the aerodynamic and dynamic characteristics of rotor systems have been somewhat simplified for convenience. To more adequately define a rotor system, the model should include terms to represent the boundary layer, skewed flow, oscillitory aerodynamics, etc. An investigation should be conducted to show the effect of these and other changes on the mathematical model.

9. Recommend that an attempt be made to show the effect of the various components, that make up a rotor system, on the dynamic and aerodynamic characteristics of such a rotor. The measurement of pressure distributions over rotor blade should continue. Additionally, tests of adequately instrumented rotors, should be made, as an example, to measure side, lift and drag forces.

10. It is recommended that studies be made to define the handling qualities/control system requirements for high speed rotary-wing aircraft, and to investigate the influence of these control system requirement on aircraft dynamic loading.

11. Recommend that analytical methods be developed backed by rotor system tests which would provide an accepted method for substantiation of freedom from flutter type instabilities of the main and tail rotors in forward flight.

12. Recommend that a specialist meeting such as the CAL/TRECOM Dynamic Loads Symposium be conducted on possibly an annual basis.

AREAS OF FUTURE RESEARCH RECOMMENDED BY THE V/STOL PANEL

AREAS OF FUTURE RESEARCH RECOMMENDED BY THE V/STOL PANEL

The panel review of the prepared presentations and of the audience's comments resulted in the following recommendations which were concurred in by all members of the panel.

Recommended Areas for Future Research

1. Vigorously continue efforts to establish landing surface design criteria, particularly with regard to surface undulations and bearing capability. (This recommendation stemmed from its significance in aircraft structural design considerations rather than from its significance relative to runway preparation.)

2. Conduct studies relative to limiting sinking speed of V/STOL aircraft comparable to studies that have been conducted in the past relative to limit sinking speed of conventional aircraft.

3. Develop appropriate procedures for predicting dynamic loads on fans and/or propellers and adjacent structures in transition flight.

4. Extend procedure for analyzing and/or predicting propeller whirl stability including the effects of unsteady aerodynamic loads, blade flexibility and possibly the combined effects of propeller and wing aeroelastic phenomena.

5. Continue investigations of supercritical shafting.

6. Continue studies of methods for predicting blade stall flutter and coupled resonance frequencies.

7. Install VGH recorders (or their equivalent) in representative numbers of early production VTOL airplanes (when they become available) for the purpose of obtaining environmental information on such aircraft.

8. The Army should periodically sponsor symposia similar to the CAL/TRECOM Symposium, not only in the dynamic loads field but in other fields of importance to aircraft design as well.

ADDRESS BY MAJOR GENERAL WILLIAM J. ELY

USA DEPUTY COMMANDING GENERAL

Army Materiels Command

Washington, D.C.

ADDRESS BY MAJOR GENERAL WILLIAM J. ELY

I am glad to have the opportunity to speak to you this evening. I intend to describe briefly some of the events that have taken place in the Army as a result of the recent reorganization of the Department of the Army and establishment of the Army Materiel Command. I will give primary attention to the R & D field.

About two weeks ago, on 14 June, we celebrated the 188th anniversary of the founding of the U.S. Army. In its nearly two centuries of service to the Nation since that founding in 1775, there have been many changes in the Army's structure, equipment, and its doctrine, all aimed at improving its combat readiness and effectiveness.

Back in 1861, for example, and four years before Cornell University was founded, an official balloon corps was organized as a unit in the Union Army to observe Confederate movements during the Civil War. Since reports from the balloon were sent to the ground by means of telegraph wire, or by mirrors, the balloon corps came under the administration of the Signal Corps -- the Army agency responsible for communications.

In the period that followed the Civil War, and up to the 1900's, ballooning as a sport spurred interest in aeronautics. But because of the balloon's limitation, military interest shifted during this period to the experimental work being conducted by the Wright Brothers at Dayton, Ohio. And, as we all know, Orville Wright succeeded in flying the impressive distance of 120 feet at Kitty Hawk in 1903 and shortly thereafter, the Army established an Aeronautical Division under the Chief Signal Officer for the purpose of studying the "flying machine" for military application.

The rest is well-known history, with the Signal Corps giving up its aviation responsibility in 1918, when the Army Air Service -- later to be known as the Army

Air Corps -- was formed.

Last year the Signal Corps again relinquished some of its responsibilities -- as did some of the other Army Technical Services -- with establishment of the AMC. The new AMC organization is oriented towards the solving of R & D problems as well as other problems in the logistics field and represents a determined effort to build a vastly improved and more effective Army.

Last year's reorganization of the Army, which brought the Army Materiel Command into being was a functional one, associated with the major elements of the Army's mission, which I will reduce to four basic elements for simplicity.

First, the Army must develop "doctrine", that is, it must determine "how" it is to fight whenever it may be called upon to do so, in defense of the United States.

Next, the Army must have "personnel" with which to fight and the management of this resource is of utmost importance at all times.

Third, the Army must be adequately "equipped", and the wherewithal to fight must be acquired.

Finally, the Army must "train" its troops in the use of this doctrine and materiel, and the integrated management of all four missions must provide military units ready to fight wherever needed throughout the world.

To accommodate these functional parts of the total Army mission, there are in the new organization four principal operating agencies, each responsible for a specific part of this mission.

First - The Combat Developments Command located at Fort Belvoir, Virginia is charged with establishing "doctrine" - how the Army will fight - and what kind of equipment it needs.

Second - The Office of Personnel Operations is responsible for providing "manpower" - officer and enlisted.

Third - The Army Materiel Command provides and maintains the equipment required for the "troops" to support the "doctrine". This command, as I have indicated, absorbed the "materiel" roles of the former six technical services -- Quartermaster, Ordnance, Chemical, Signal, Engineers and Transportation Corps.

Finally - The Continental Army Command at Fort Monroe is responsible for the "training" mission. In other words, it takes the inputs - doctrine, personnel and equipment - and delivers training fighting units.

The AMC has been given authoritative control over all Army wholesale materiel operations. It is responsible for all operational aspects of R & D, testing, procurement, production, supply and maintenance, as well as the operations of certain laboratories, arsenals, proving grounds, depots, test facilities, procurement activities and offices. This arrangement of functions gives us a much more effective wholesale logistics operation than in the past.

As you would surmise, the job at AMC is a big one. The fact that we are responsible for annual expenditures of around 8 billion dollars is only one indication of the size of our job. In addition, we had a starting inventory of weapons and materiel estimated to be worth 23-1/2 billion dollars. We have 177,000 personnel, of whom only 21,000 are military, located in some 250 installations and activities.

Most of these installations and personnel are organized into seven major subordinate commands, each headed by a General Officer.

Five of the commands are oriented toward hardware. Their alignment

follows the traditional job of the Army to move, shoot, and communicate.

We have a Mobility Command with headquarters in Detroit to handle the "movement" requirement.

The "shooting" function is broken into three commodity areas - a Weapons Command at Rock Island - a Munitions Command at Picatinny Arsenal, New Jersey, and a Missile Command at Huntsville, Alabama.

The fifith commodity command - The Electronics Command at Fort Monmouth, New Jersey, is responsible for communications hardware.

Supporting these five commodity commands is a Test and Evaluation Command at Aberdeen, Maryland, responsible that the equipment provided by the commodity commander is in fact suitable for field use.

And our seventh command, the Supply and Maintenance Command, is located in Washington, and is responsible for distributing equipment and keeping it in operating order. Its orientation is toward the "user" of Army materiel.

Now that I have reviewed our general organization and mission, I will outline our system of Research and Development. When the assignment of activities previously performed by the various technical services was reviewed, it became apparent that certain AMC labs performed work of a fundamental nature, or of such broad scope, that they did not fit within any one of the commodity commands. Therefore, we have placed eight (8) research labs directly under the R & D staff element of the AMC Headquarters. This has been done so that their Army-wide functions can be supervised from that level and further, to assure that their capability is readily available to all segments of the AMC structure.

The eight laboratories perform work in the fields of basic and applied research; they are not associated with a specific commodity command and they

work in disciplines or areas which cover Army-wide requirements. Each laboratory works in areas important to the Army and provides support to the commodity commands. In this respect, their work is of the contractor-type operation for the commodity command concerned. Research directly associated with a particular commodity area is accomplished in laboratories or agencies within the commodity commands. These commodity commands also accomplish development, engineering, production planning, and production work. Major testing activities, including engineering and user tests, are accomplished by the Test and Evaluation Command.

These eight "independent" laboratory complexes possess an important part of the Army's in-house capability for basic and applied research. Every one of the eight is outstanding in its assigned field.

Let me tell you what the laboratories are:

THE FIRST ONE IS THE U.S. ARMY BALLISTICS RESEARCH LABORATORY complex which is located at Aberdeen Proving Ground, Maryland. This organization conducts basic and applied research in ballistics and in the related fields of physics, chemistry, mathematics, and engineering.

It provides expert knowledge in the fields of interior, exterior, and terminal ballistics, instrumentation for ballistics measurements, calibration techniques, weapons system analyses, and computation of firing tables.

These labs are equipped with one of the finest assemblies of equipment and facilities for ballistic research to be found anywhere in the free world. They provide unparalleled opportunities for professional freedom and research on projects of greatest importance to the national defense.

FOR EXAMPLE, THE BALLISTICS MEASUREMENTS LABORATORY is concerned with the flight of missiles, satellites, and space probes used as flying

laboratories for investigating the upper atmosphere. It conducts research leading to new methods for obtaining flight data and new techniques for studying atmospheric constituents.

THE NEXT LABORATORY IS THE U.S. HUMAN ENGINEERING LABORATORY COMPLEX, which is also at Aberdeen. It is the principal agency for human factors engineering in the Army Materiel Command.

You'll be interested to know also that it is the largest organization of its kind in the Department of Defense. Its function is to perform basic and applied research in human factors engineering of overall interest to the AMC, and to assist the Army Materiel Command design agencies in the application of human factors engineering principles to end item and system designs.

THE COATING AND CHEMICAL LABORATORY is also located at Aberdeen and conducts research on automative chemicals, organic coatings, and conversion coatings and cleaners. This is a small laboratory but very competent in its field. The laboratory performs basic and applied research and engineering investigations in the fields of automative chemicals, organic and semi-organic coatings, conversion coatings and cleaners.

THE NEXT COMPLEX IS THE U.S. ARMY NATICK LABORATORY. It was formerly known as the Quartermaster Research and Engineering Center at Natick, Massachusetts. It conducts research on the operational capability of the fully equipped individual soldier under varying degrees of operational and environmental stress.

It also pursues research in the fields of biology, chemistry, and physics, pertaining to the design and development of end . ems such as food and clothing.

This important research provides greater protection and effectiveness for the individual combat soldier.

The U.S. Army Natick Laboratory might well be identified as the "laboratory concerned with the individual soldier", since it is the laboratory which devotes its entire attention to food, clothing, combat shelters, air delivery of supplies, and handling of supplies in the combat theater.

In the never-ending search to maintain the reputation that "the American soldier is the best fed soldier in the world," the Natick Laboratory is taking a leading part in the preservation of food by irradiation. Accomplishment of this objective will not only provide the soldier with meats, fruits and vegetables heretofore impossible to supply without an enormous attendant refrigeration capability, but will also provide the soldier with food of much higher quality and acceptability.

The research on irradiated food has progressed to the point where clearance for one meat item -- bacon -- for unlimited feeding has been received from the Food and Drug Administration.

In the clothing area, the development of the Natick Laboratory has extended the cold climate endurance capability of the American soldier many-fold, while at the same time reducing the weight and complexity of his gear.

ANOTHER COMPLEX OF THE EIGHT IS THE COLD REGIONS RESEARCH AND ENGINEERING LABORATORY which is located at Hanover, New Hampshire. It carries out research and experimental engineering in snow, ice and frozen ground. You'll be interested to know that it also conducts research in earth physics.

The last of our eight research laboratories is the Nuclear Defense Laboratory (NDL) located at Edgewood Arsenal, Maryland.

NDL provides technical information pertinent to the field of radiological defense and health physics to agencies responsible for the development of clothing, vehicles, protective structures, and other end items which might be incorporated into nuclear protection.

Additionally, NDL provides technical information and assistance in the field of nuclear defense and health physics to Army agencies responsible for developing concepts, policies and doctrines. The laboratory expends approximately 75% of its resources to conduct research in the nuclear weapons effects research areas of fallout, residual radiation, and thermal phenomena.

As I said in the beginning, the eight laboratories I have discussed are working in the fields of basic and applied research. These laboratories are not directly associated with a specific commodity command. They are working in disciplines or areas which cover Army-wide requirements, and we plan to concentrate on and improve the capabilities of these laboratories.

When considering the research and development potential held within the confines of our eight "independent" laboratories we do not discount the importance of the research performed in commodity command laboratories merely because their work is directly associated with a particular commodity area. As you realize, their research is predominately supporting research. However, we do promote and encourage more fundamental work in those laboratories which have the competence and facilities demanded to perform the work.

Now for some philosophy with regard to our approach to research and development in aerodynamics. First of all, one of the outstanding characteristics of our modern technological society is a reverence for time. We want speed. We want to be ahead of our competitors -- and keep ahead.

Nowhere is this desire more sharply focused than in our research and development business. Nowhere is it more clearly emphasized than in the reduction of "lead time" in the development of military hardware. Clear and definitive requirements have decreased significantly the time required to formulate development plans, and improved program planning techniques have shrunken the time from conception of a program to delivery of a weapons system.

There is a very promising path to even further savings in time, however, which has not been pursued sufficiently in the past. That path lies in the way research is regarded, fostered, and guided. In AMC, our commitment to a vigorous research program is based upon two corollaries:

Corollary Number One: The earlier we discover a new fact or a new scientific concept, the greater will be our time advantage. To achieve this is the primary objective of our basic research effort in AMC -- an effort aimed at increasing, at an accelerated rate, our storehouse of fundamental knowledge, and by so doing, ensuring that we stay a jump ahead in the race for time.

Corollary Number Two: The results of our basic research efforts, in turn, must be used to accomplish specific objectives. The quicker we apply our knowledge to a specific project to fulfill a military requirement, the greater again will be our time advantage. To achieve this advantage is the primary objective of our applied research program in AMC.

In the field of aeronautical research, we now recognize the fact that -- for logical reasons -- we can no longer rely upon the Navy and Air Force to provide us with advanced technology for low speed aerodynamics essential to future Army developments. Accordingly, a cooperative effort -- begun last fall -- between the Army Research Office, the Chief of Research and Development, and the Army Materiel Command has resulted in a document defining areas of endeavor of low speed aerodynamics necessary for supporting future Army development in this area.

This document, referred to simply as the Army Aeronautical Research Program, recognizes the fact that dynamic air loads in the field of rotary wing aircraft is an area requiring much greater effort. Additionally, since VTOL aircraft are more weight sensitive than conventional aircraft types, the load spectrum must be even more accurately defined for them. Incidentally, releasable portions of this document will soon be made available to those of you in industry and science who are working in this area.

Solution of the problem of air loads for these types of aircraft will, as General Clark indicated in his opening remarks, require concentrated effort from many disciplines, but the dynamist will be required to integrate and apply their efforts in gaining a satisfactory end product. We look to you for help, then, in providing the soldier with simple, rugged, economical aircraft which will improve his combat effectiveness.

In the simplest terms, the air mobility the Army is seeking is the organic capability to move men, supplies, and firepower within the Army's battle area by the most modern of means -- helicopters, for example. In so doing, we will gain new freedom of maneuver, new ability to resupply fighting forces, new capabilities

for battlefield reconnaissance, and new opportunities to apply decisive force with tactical surprise. These gains are vital necessities.

This is as inevitable as the turn from the horse to the truck. It is as necessary as the addition of the HONEST JOHN rocket to our weaponry. We need older tools for certain operational spheres, but new means are essential if we are to gain a mobility differential over our enemies. Air mobility may ultimately produce a tactical revolution as profound as the initial mechanization of land warfare. It is certainly indispensable to a modern ground force.

The basic premise on which AMC was established was that one new and effective weapon or piece of equipment in the hands of the soldier is worth a hundred on the drawing board. But inherent in the challenge provided by this premise is that of consideration for the taxpayer's pocketbook. As the Chief of Staff, General Wheeler, has stated, "We run continuing risk of pricing ouselves off the battlefield because the whole dollar trend in equipment procurement is spiraling upward." Therefore, he pointed out, the "question of cost effectiveness has definite bearing on air mobility."

In short, demands upon available funds today are greater than ever before. Because of this, we are making every effort to insure that the areas of research engaged in by AMC, or sponsored by AMC, are truly necessary. "Nice to have" or "interesting" programs will have to go by the board. Yet this is not to say that we will not recognize the changing state-ot-the-art. In this connection, I assure you that our Aeronautical Research Program will be kept under continuous review, and in this regard, the advice and assistance of the scientific community and industry is earnestly solicited. With your valuable help, I am confident we can continue the fine progress we have made and are making in improving and increasing the air mobility of the Army.

I can best express my appreciation to you for the courtesy you have extended to me today by saying that the Army has always considered and still considers industry a truly important partner in fulfilling its materiel requirements Further, the Army Materiel Command is delighted with the cooperation and the enthusiastic support industry has given us in meeting our research and development needs.
